Optimization of the LBNF Neutrino Beam

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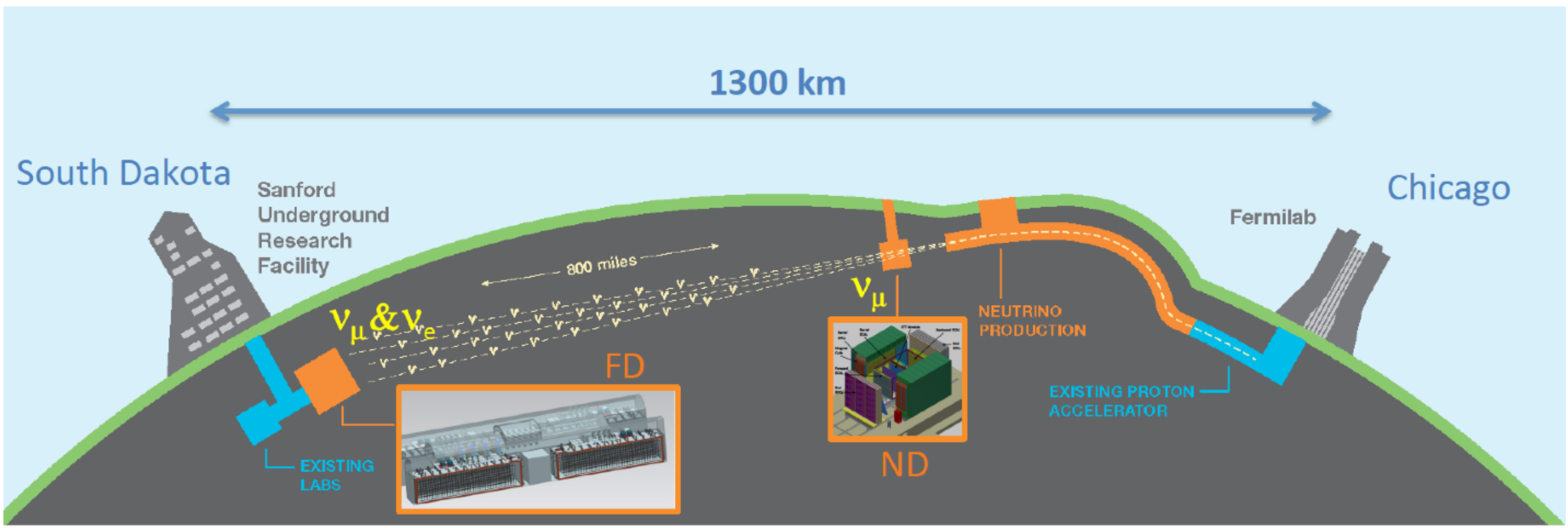
High Power Targetry Workshop

4 June 2018

Fermilab

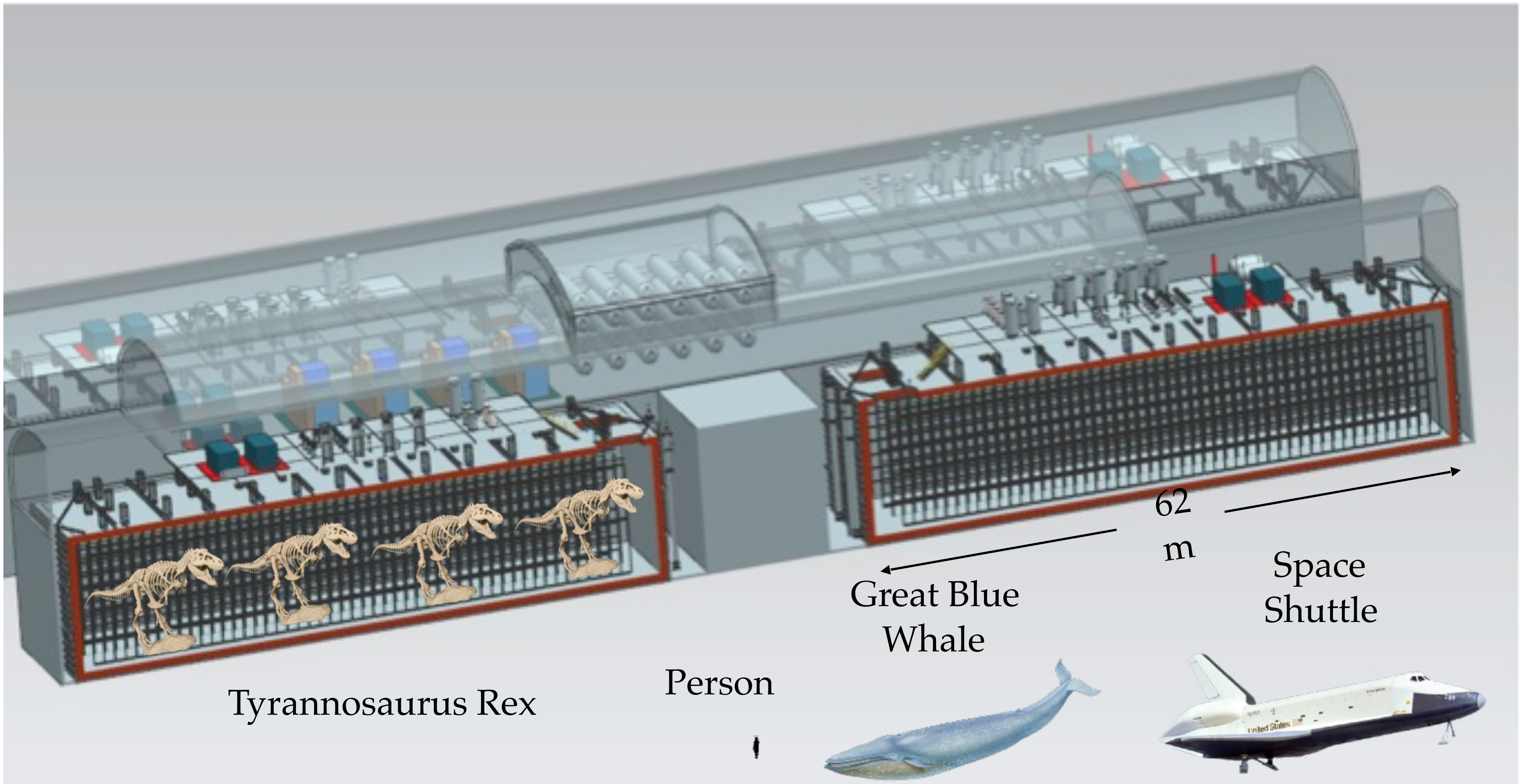
LBNF/DUNE Overview

- LBNF (Long Baseline Neutrino Facility) and DUNE (Deep Underground Neutrino Experiment):
  - Neutrinos from high-power proton beam
    - **1.2 MW from day one**; upgradeable to at least 2.4 MW
  - **Near detector** to characterize the beam
  - Massive underground Liquid Argon Time Projection Chambers
    - **4 x 17 kton** (fiducial mass of more than 40 kton)



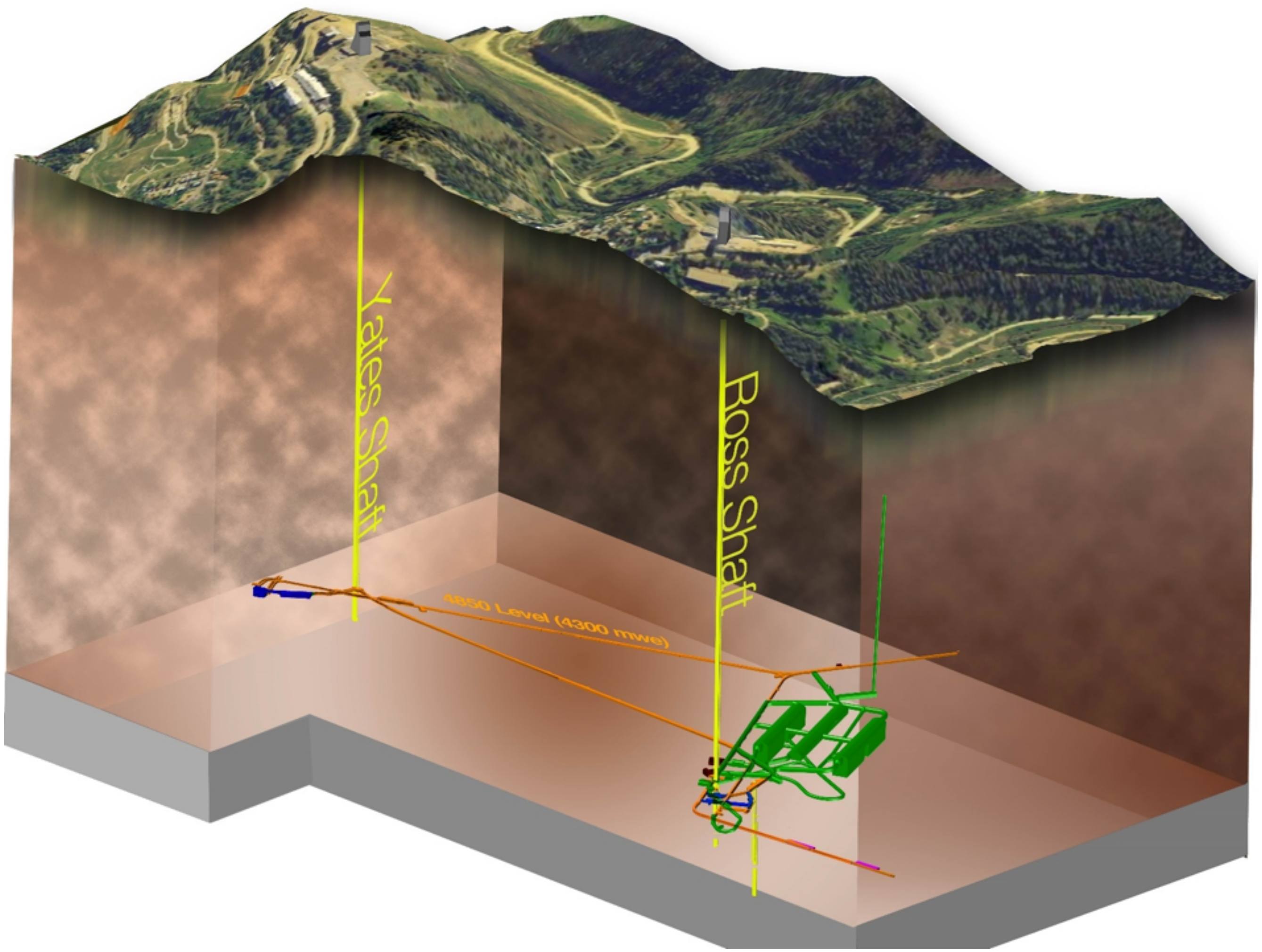
LBNF/DUNE Overview

Some size comparisons of the far detector:



LBNF/DUNE Overview

The far detector will be nearly a mile underground



LBNF/DUNE Science Program

- Neutrino Oscillation Physics
  - Search for leptonic (neutrino) **CP violation**
  - Resolve the **mass hierarchy**
  - **Precision oscillation** physics
- **Nucleon Decay**
- **Supernova** physics and astrophysics
  - 3000 ve events in 10 sec from SN at 10 kpc
- Plus **many other** topics
  - neutrino interaction physics, atmospheric neutrinos, sterile neutrinos, WIMP searches, Lorentz invariance tests, etc.

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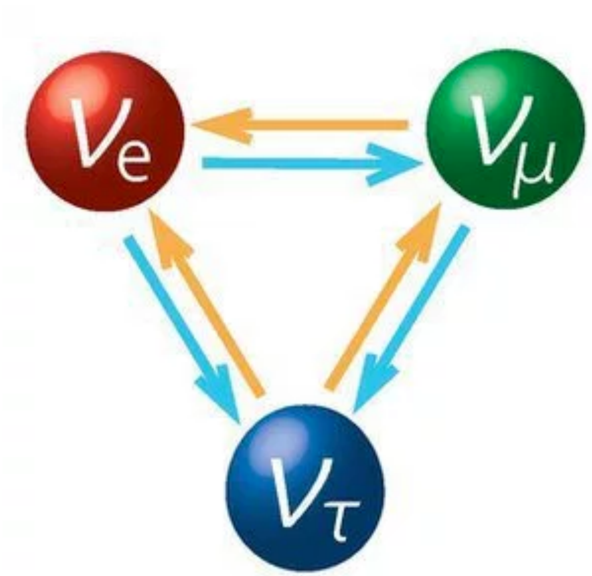
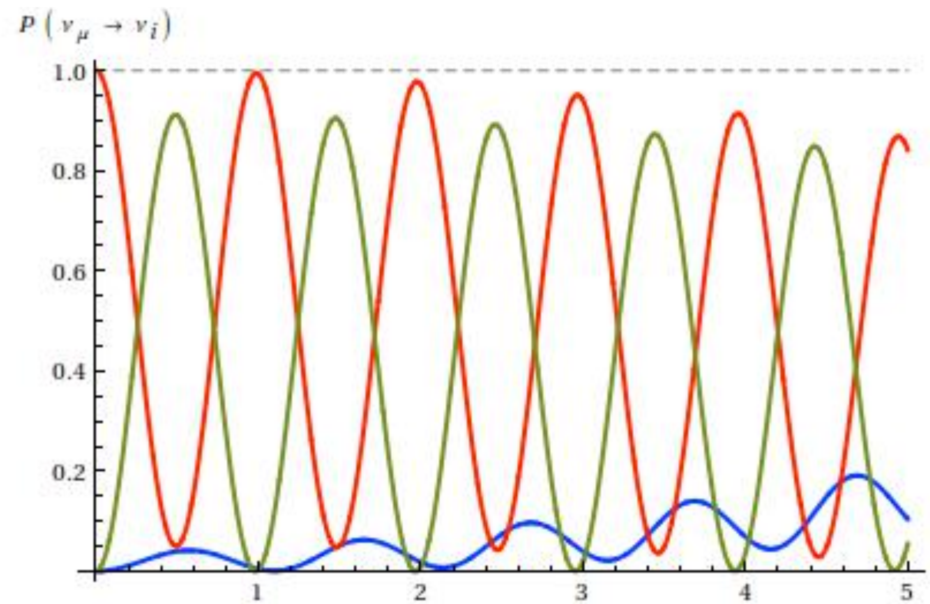
This is why we need to build a neutrino beam of unprecedented intensity

LBNF/DUNE Science Program

- DUNE will measure oscillations of neutrinos:



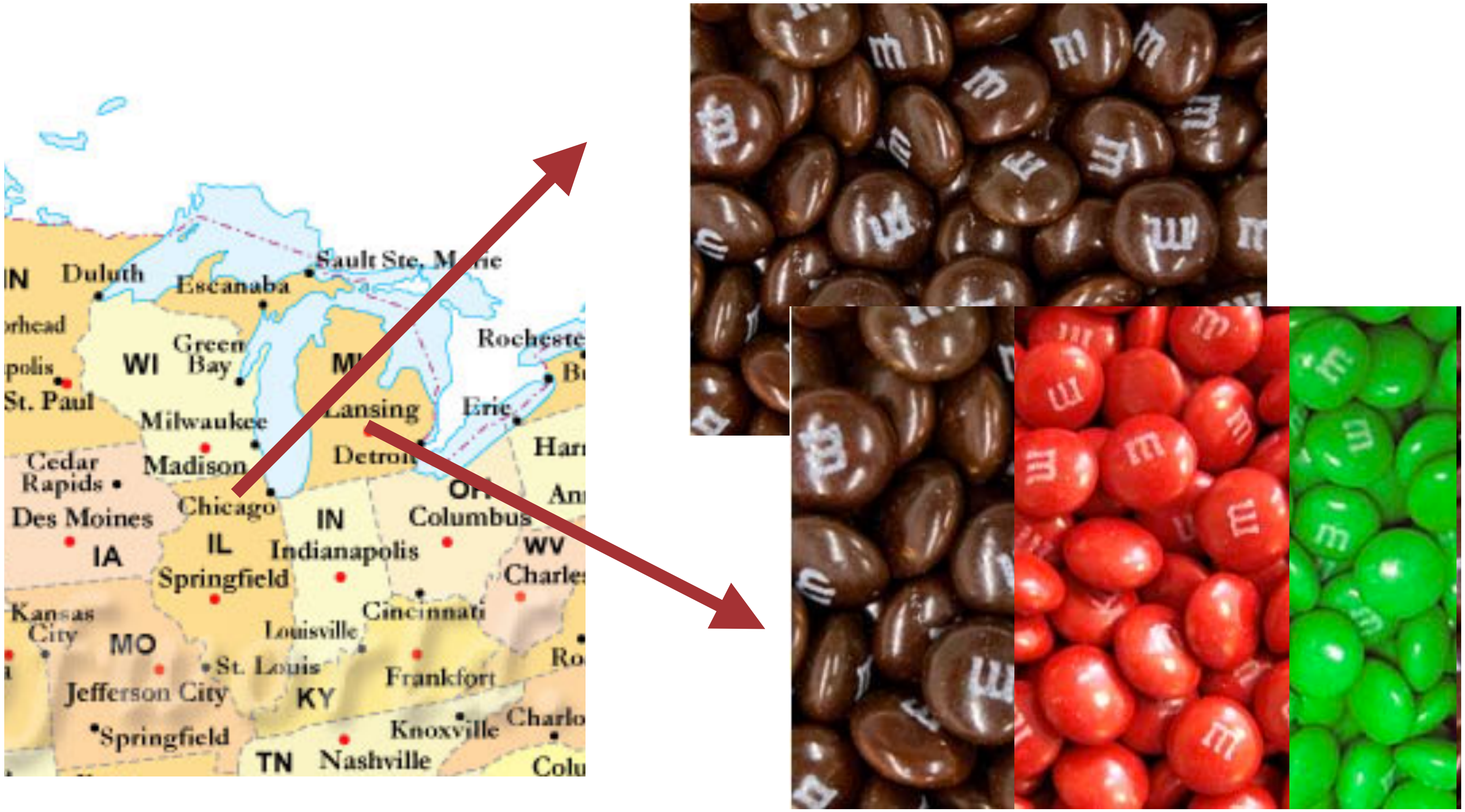
Probability of a Muon Neutrino Oscillating to an **Electron**, **Muon** or **Tau** Neutrino



Distance Traveled / Energy (km / MeV)

LBNF/DUNE Science Program

- Neutrino Oscillations are *very* odd behavior:



LBNF/DUNE Science Program

- And this is physics beyond the Standard Model — we *must* investigate it!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS Matrix:
Elements are functions of three mixing angles (θ_{13}, θ_{23} , θ_{23}) and one CP-violating phase (δ_{CP})

- Some of the specific things we are trying to measure:
  - What are the values of the mixing matrix — especially, what is the value of the CP-violating phase?
  - What is the neutrino mass ordering?
  - Is the data consistent with this model?

LBNF/DUNE Science Program

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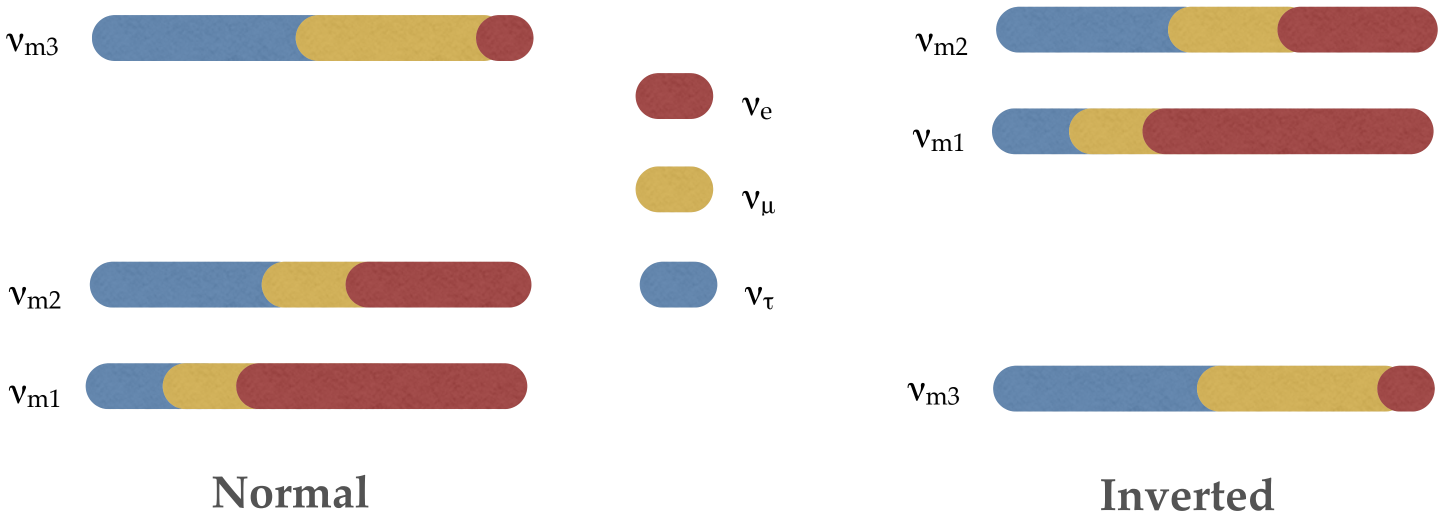

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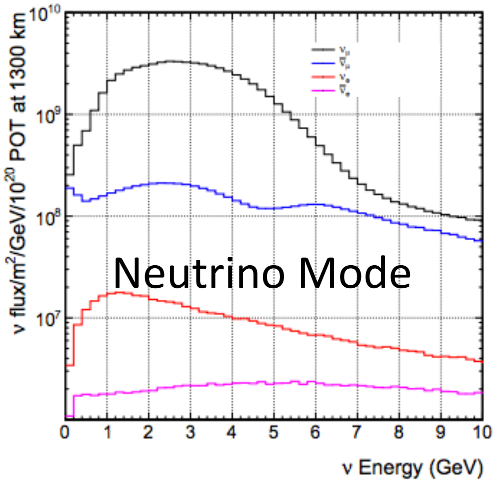
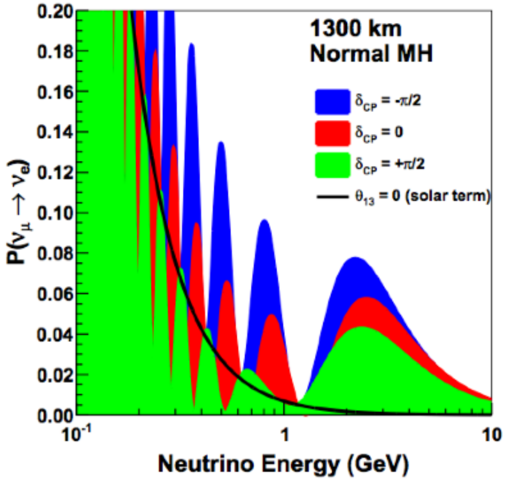
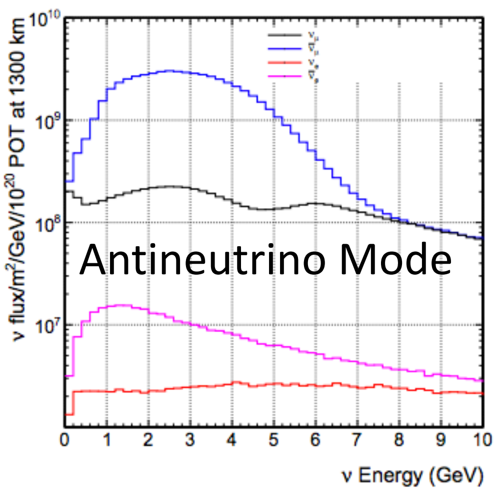
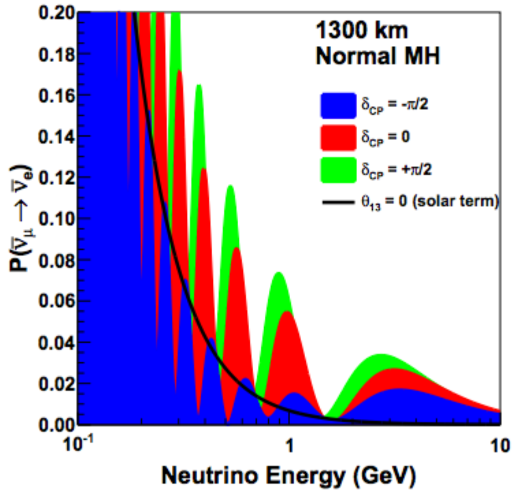
LBNF/DUNE Long Baseline Physics





Initial neutrino energy spectra will be modified by neutrino oscillation probabilities

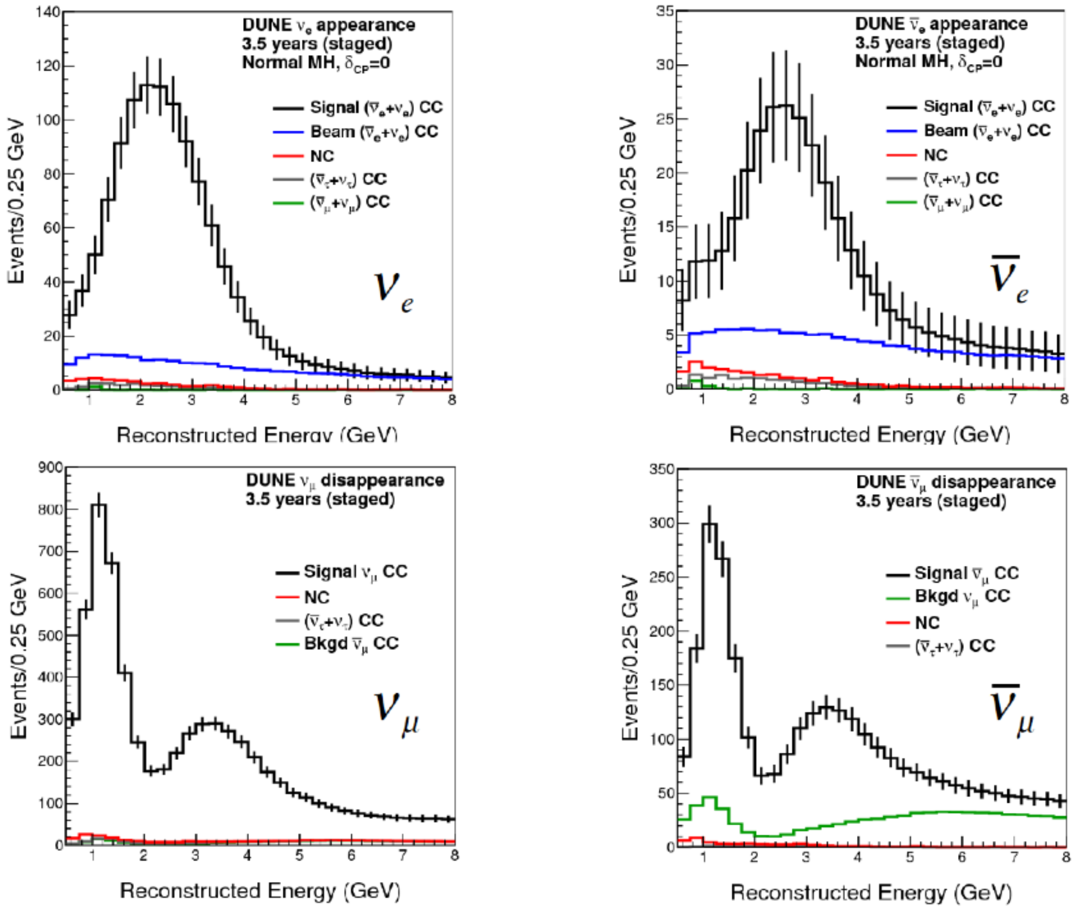




Figures from DUNE CDR

LBNF/DUNE Long Baseline Physics

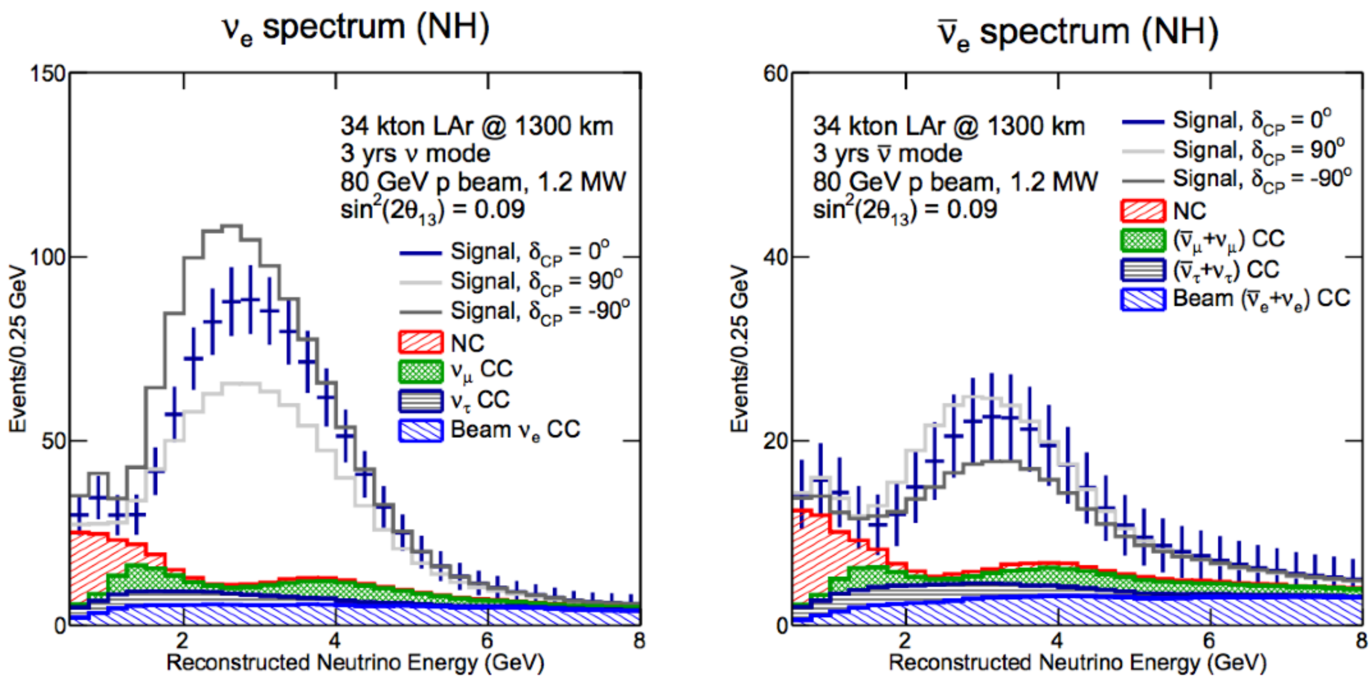
- After traveling 1300 miles and interacting in an Argon detector:



Figures from DUNE CDR

LBNF/DUNE Long Baseline Physics

- We'll be trying to detect **very subtle differences** in predicted event spectra expected for different oscillation parameters:



These are really, really old plots, but illustrate the kinds of differences we'll be trying to resolve

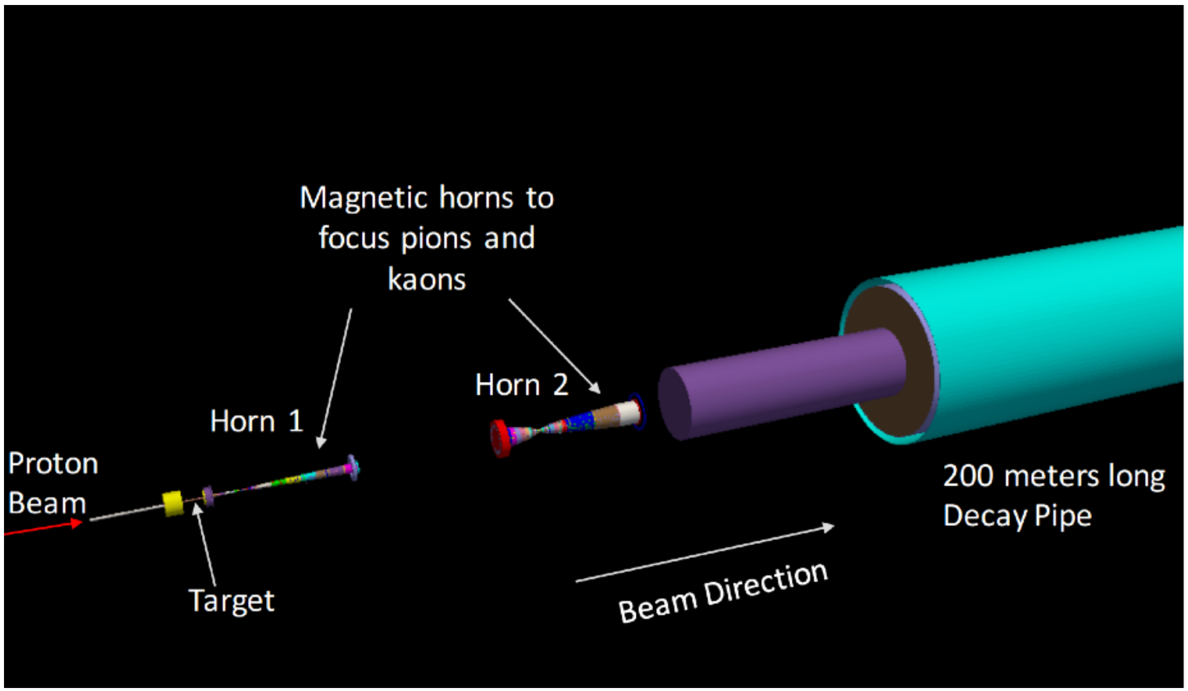
LBNF Beamline

- LBNF will use protons from the Main Injector, which will operate at 1.2 MW to star and will be upgradeable to 2.4 MW

Proton beam will be tunable between 60 and 120 GeV

LBNF Beamline

- Until recently, LBNF was currently considering **two different beamline designs:**



Reference Design

Two horns, nearly identical to those used in NuMI, run at slightly **higher current** (230 kA)

1 m long graphite fin target, similar to but not identical to NuMI target

Figures courtesy Amit Bashyal

LBNF Optimized Beamline

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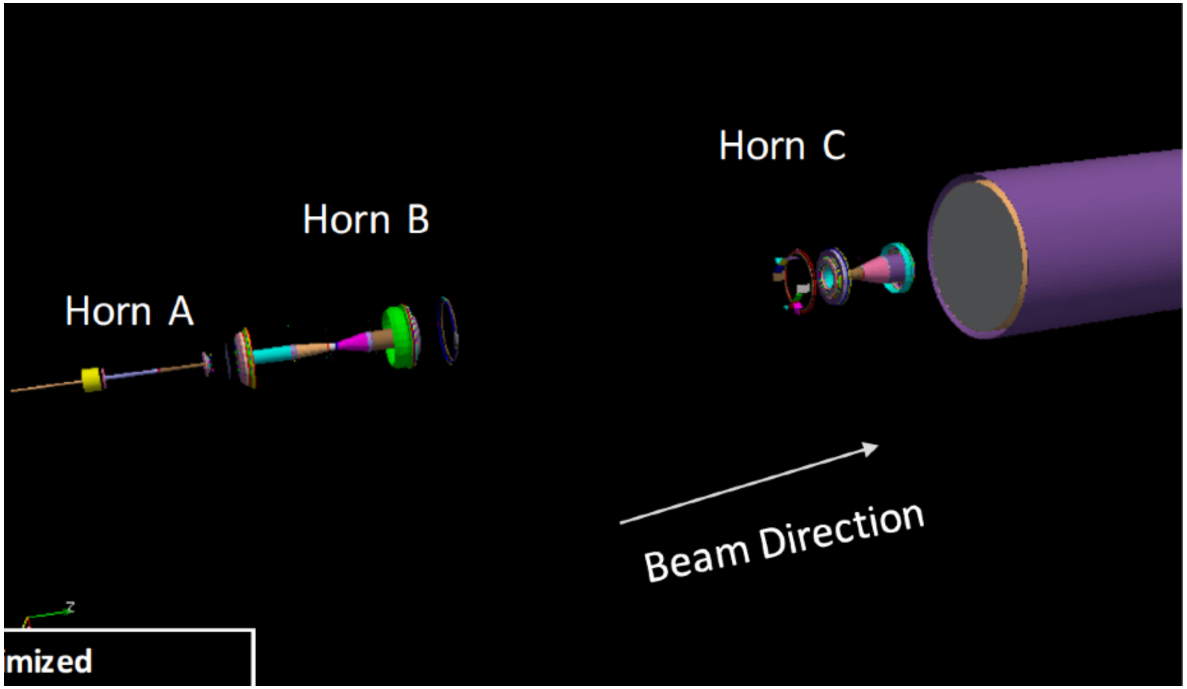


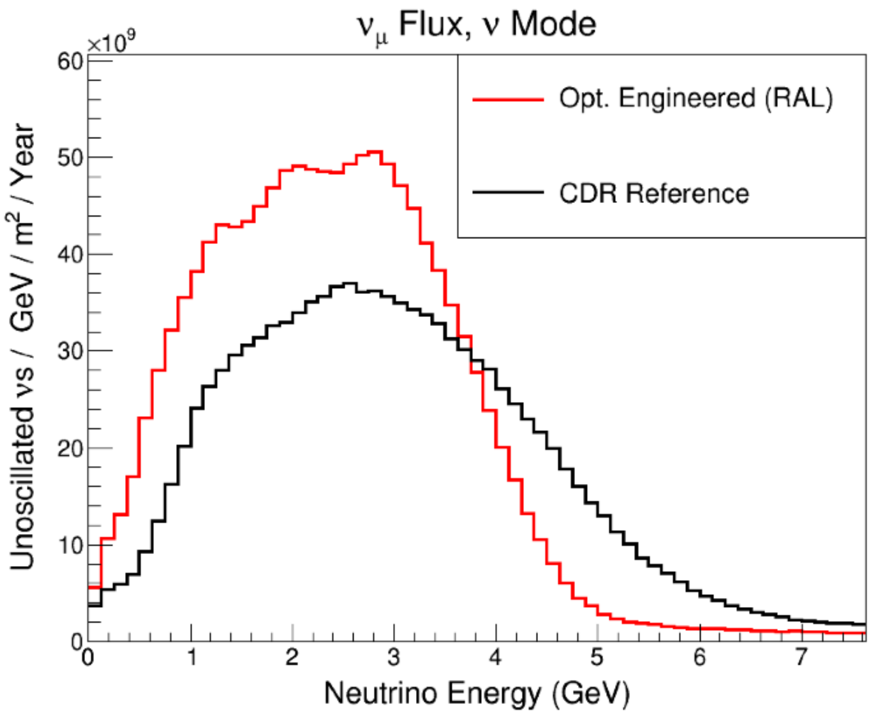
Optimized Design

Three horns, not similar to NuMI, run at **300 kA**

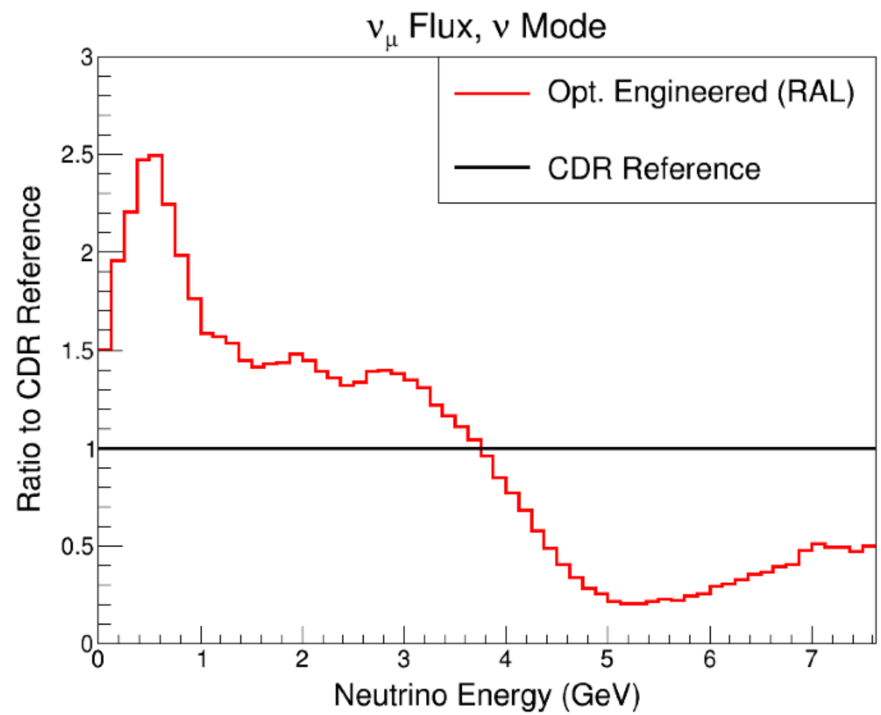
2.2 m long carbon target

Figures courtesy Amit Bashyal

Physics Performance of Beam Options



- Muon neutrino **flux is significantly improved in the optimized design** over the reference

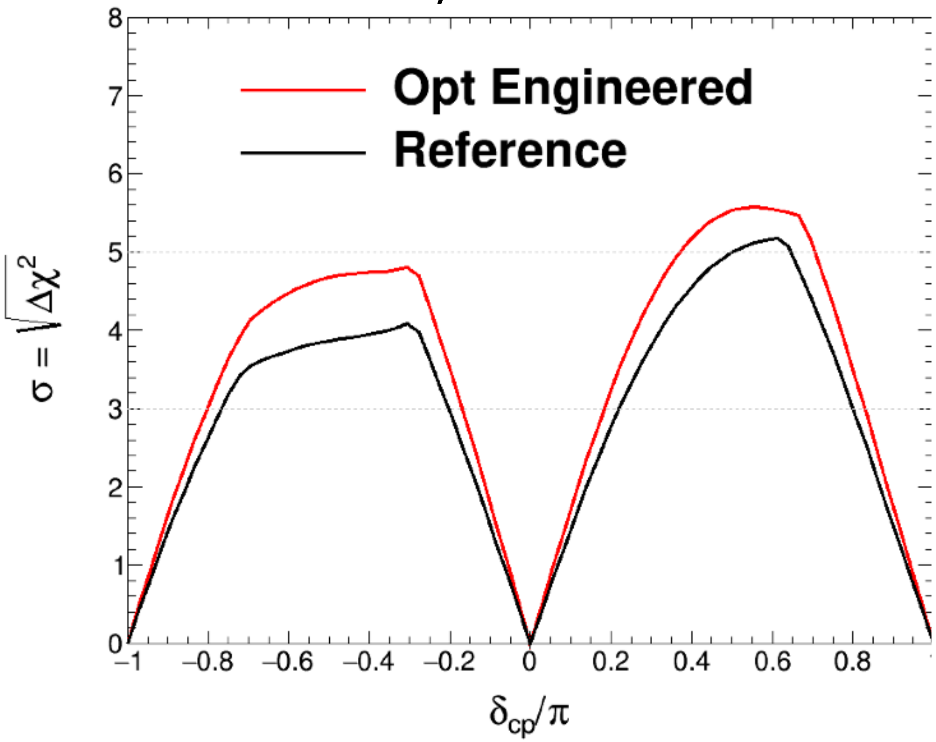


- Flux increases by 36% in the critical 1-4 GeV region
- Increase is more than a factor of two below 1 GeV

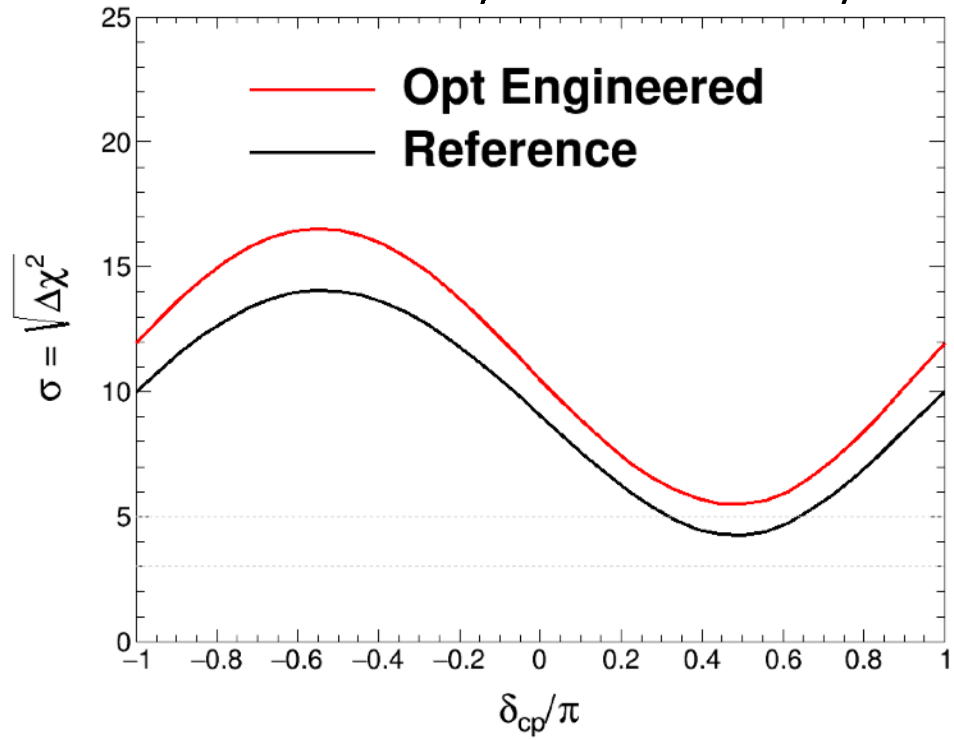
Physics Performance of Beam Options

- This translates into improvements in physics sensitivities

Sensitivity to CP Violation



Sensitivity to Mass Hierarchy

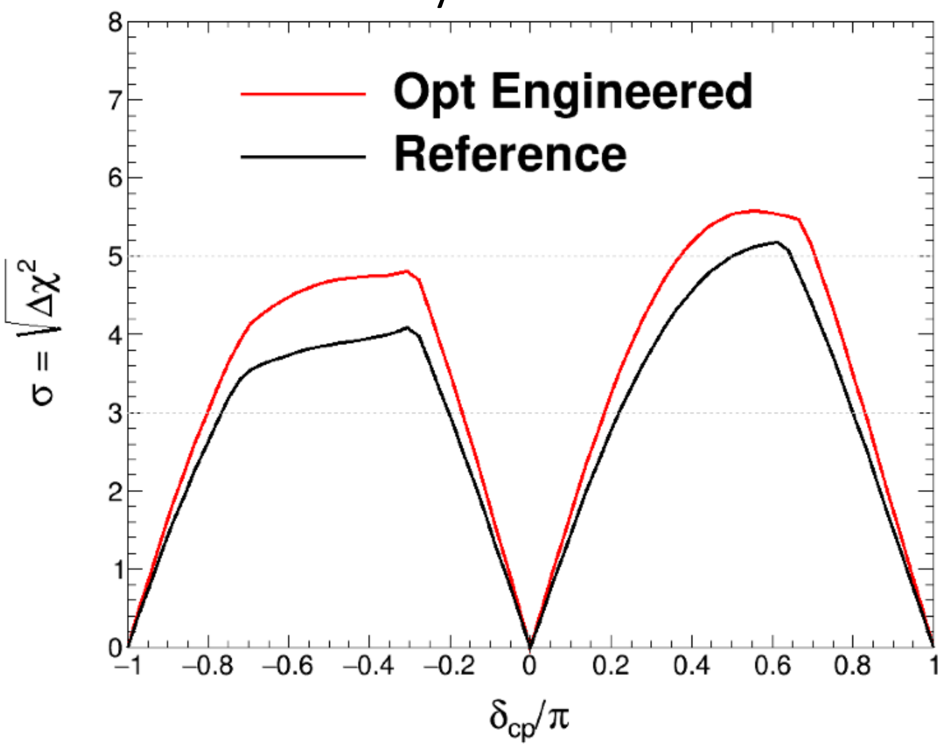


Sensitivities use CDR GLoBES setup and default parameters, and exposure of 300 kT MW years; CP sensitivity assumes a normal mass hierarchy

Physics Performance of Beam Options

- You're going to see a lot of this plot, so let's go over it briefly:

Sensitivity to CP Violation



- It shows how sensitive DUNE will be to CP violation after about 6 years
- If there is a lot of CP violation (δ_{CP} near π/2 and -π/2), DUNE will be able to clearly see it
- For smaller amounts of CP violation, the situation will be less clear

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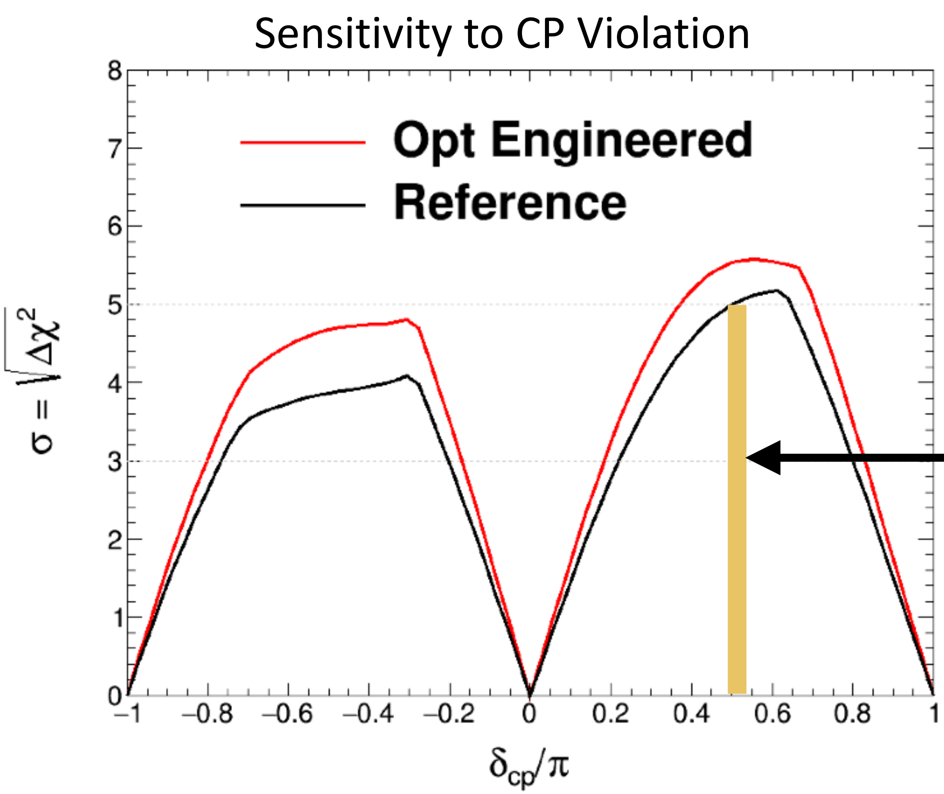

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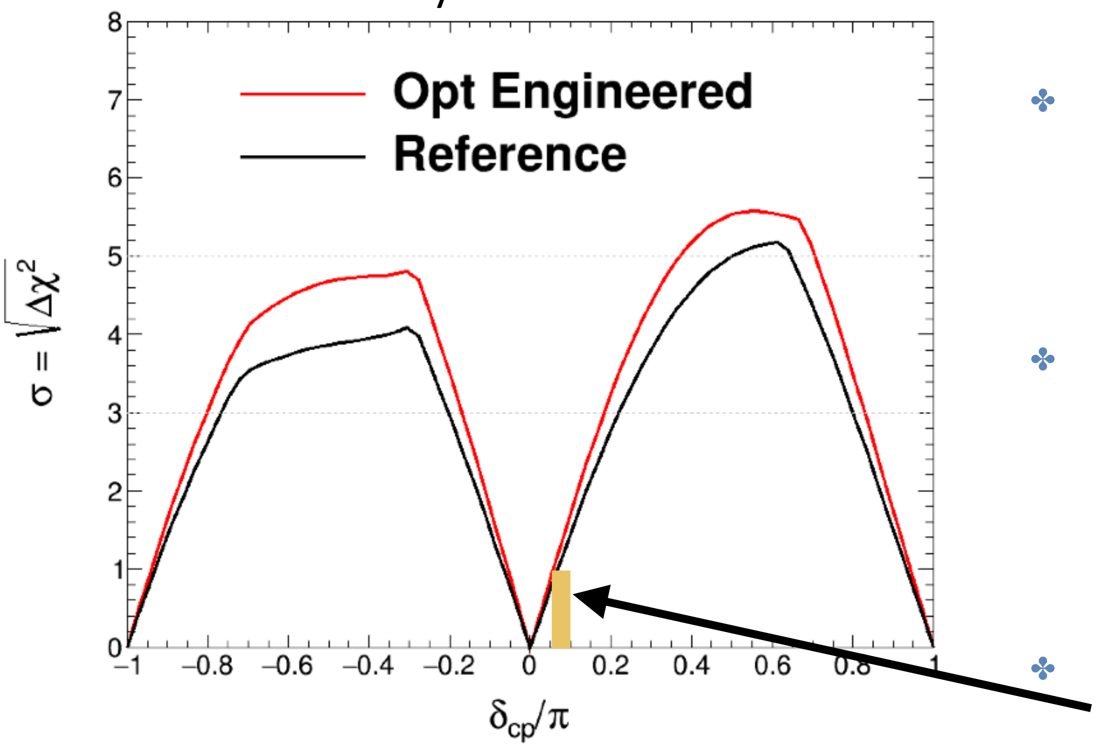

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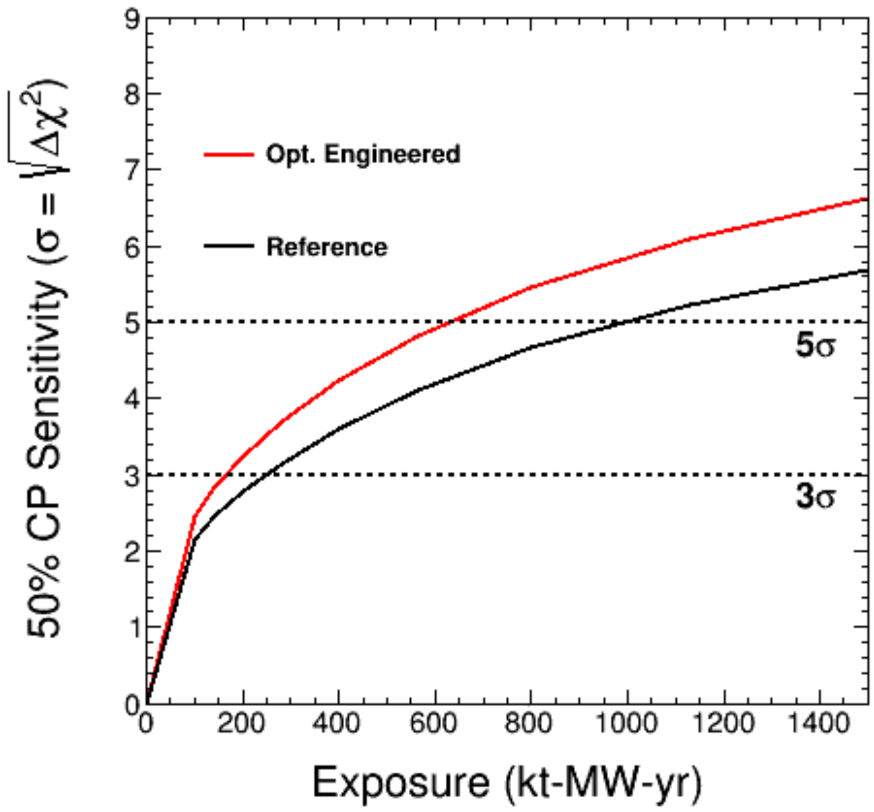
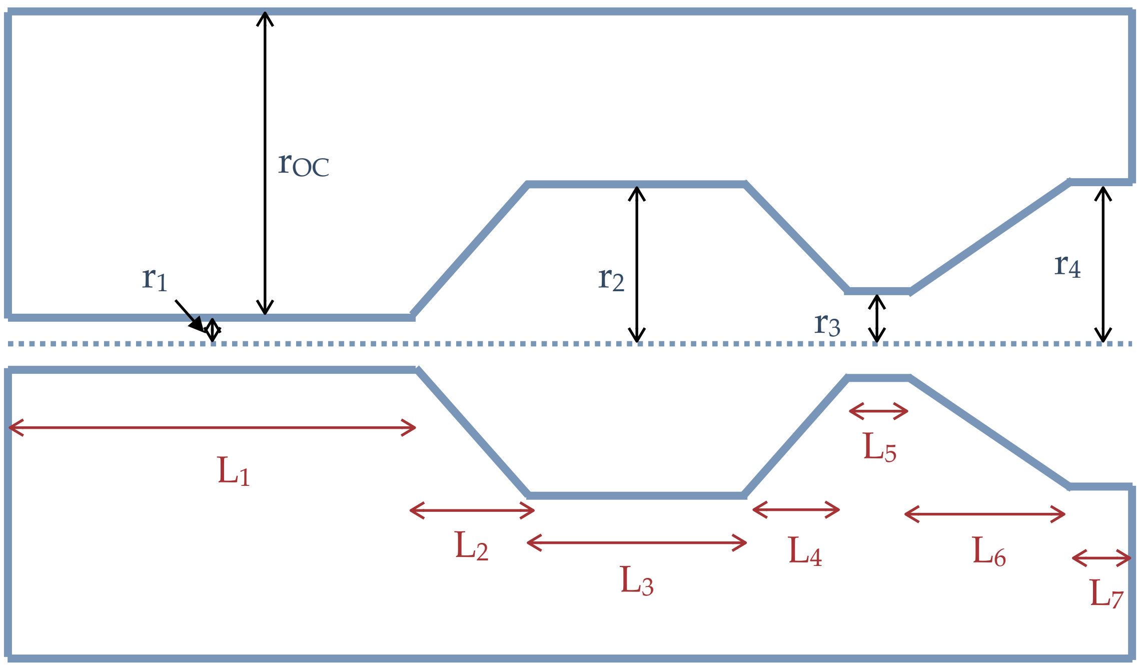
Physics Performance of Beam Options



- For some figures of merit, the improvements in time to reach physics milestones **corresponds to increasing the far detector mass by 70%** — 28 kTons of liquid Argon
- Last fall, LBNF/DUNE **made the decision to go forward** with the optimized beam design
  - Physics argument was clear
- The rest of this talk:
  - **How we redesigned the beam** to get a physics improvement equivalent to 28 kTon of additional liquid Argon

Beam Optimization

- A first step in beam optimization is identify parameters of the beam that could be changed
  - These are what we started with:



Parameters Varied:

- Horn 1 shape parameters (see figure)
- Width/length of carbon fin-style target
- Horn current
- Horn 2 radial and longitudinal scales
- Horn separation
- Proton beam momentum & radius

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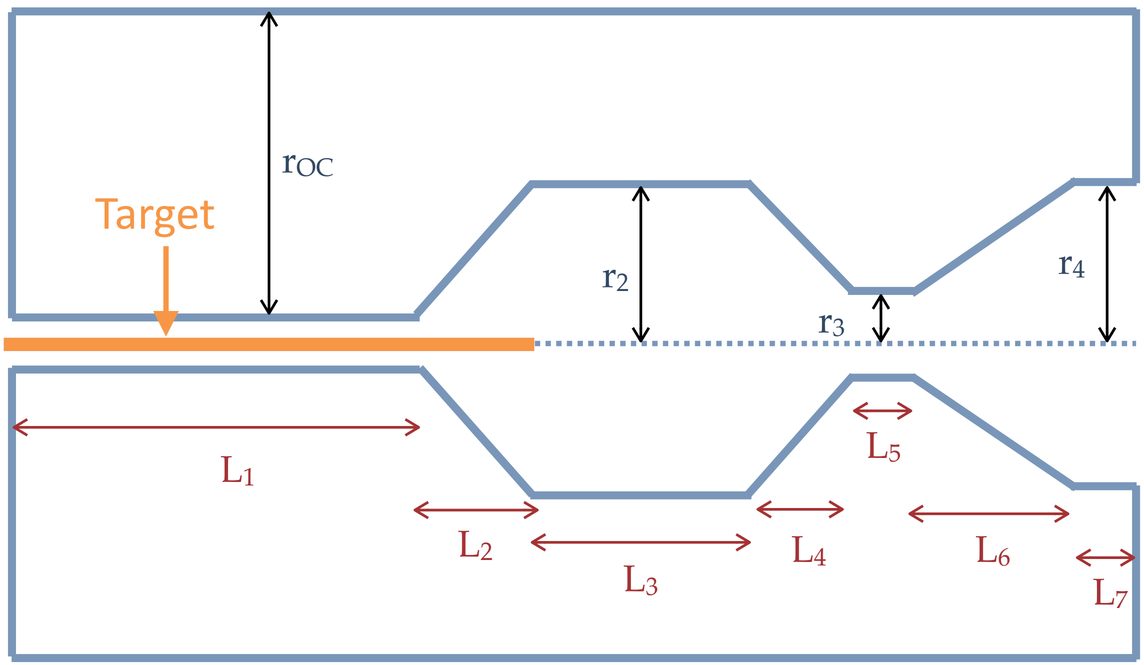

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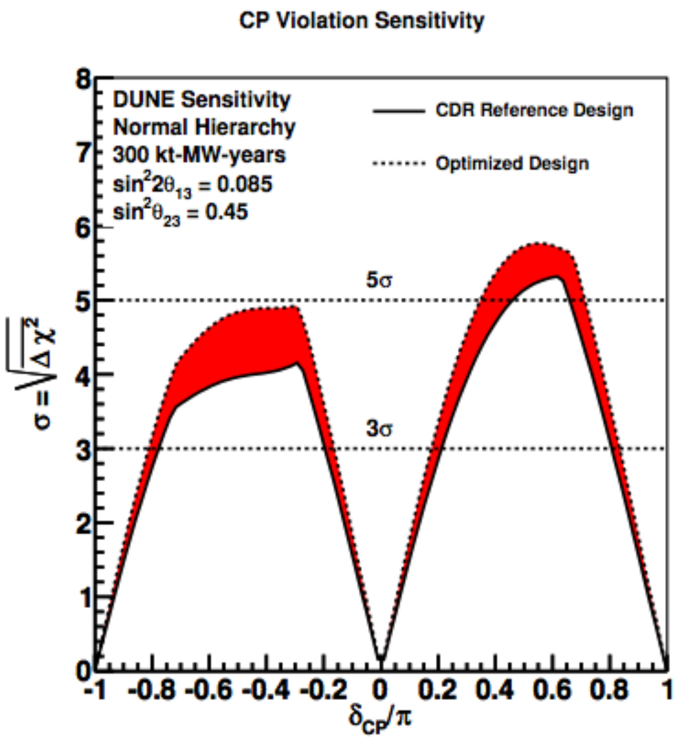
Beam Optimization

- Also need to pick one quantity to optimize
  - Although algorithms exist to optimize multiple quantities
- For LBNF/DUNE, the choice was pretty clear



CP Sensitivity is one of our most important and most challenging goals.

Beam Optimization

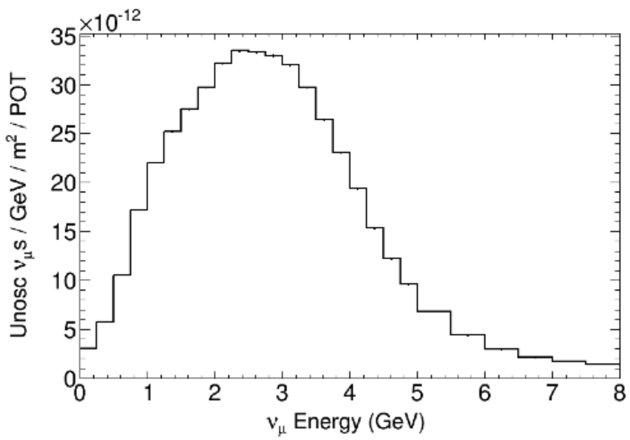
- First step in optimizing optimizing the beam to pick one quantities to optimize
- For LBNF/DUNE, the choice was pretty clear

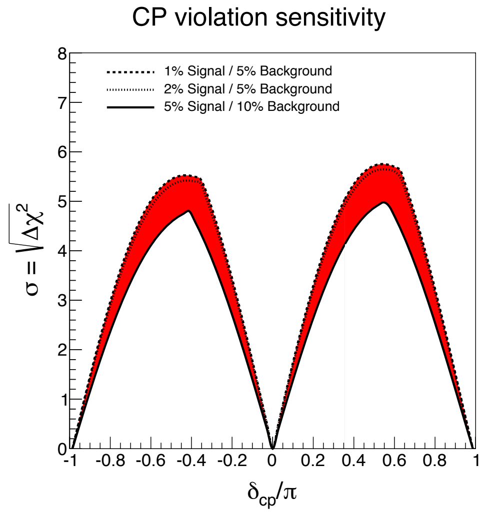
, we set as the goal a mean sensitivity to CP violation of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δCP


Building for Discovery
Strategic Plan for U.S. Particle Physics in the Global Context
Report of the Particle Physics Project Prioritization Panel (P5)
May 2014

Genetic Algorithms

- What we'd ideally do at this point would be to simulate a bunch of beam configurations, estimate the physics performance, and pick the best one:

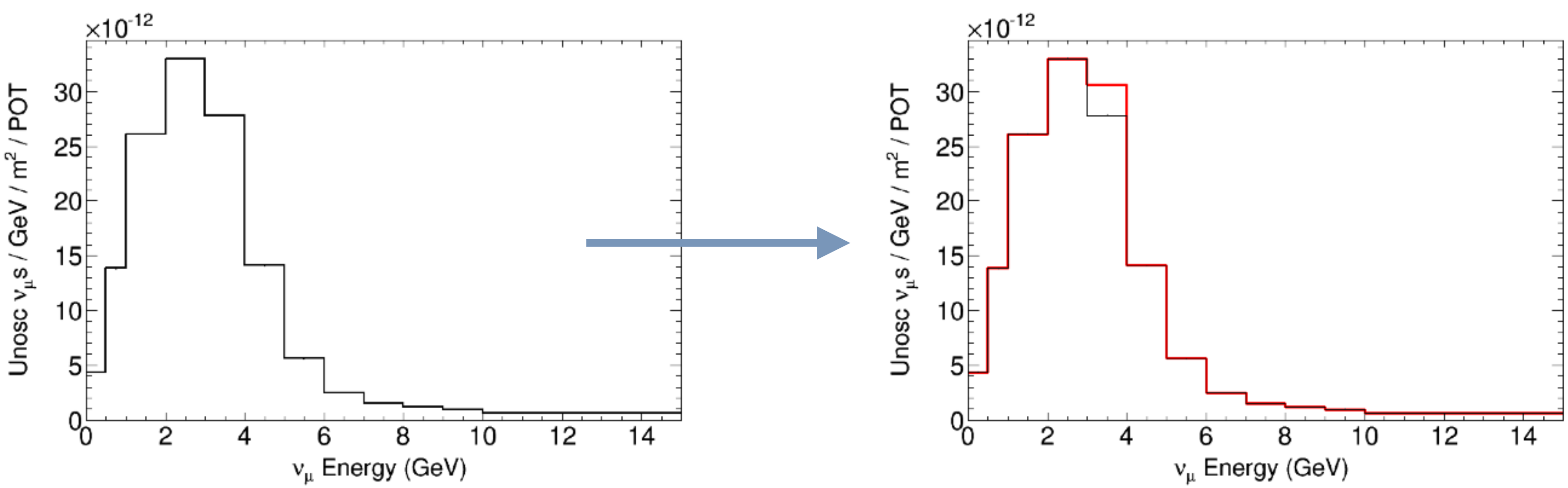




One problem: when we started this endeavor, this simulation cycle took ~ about a week

Genetic Algorithms

- But we developed a fast estimator of CP sensitivity that ran in 2 seconds (after the 1-2 hour simulation of the neutrino beam)



- We measured the change in CP sensitivity given some fixed changed in a single energy bin of the neutrino energy spectrum
- And used that information to estimate CP sensitivity for any neutrino energy spectrum

Genetic Algorithms

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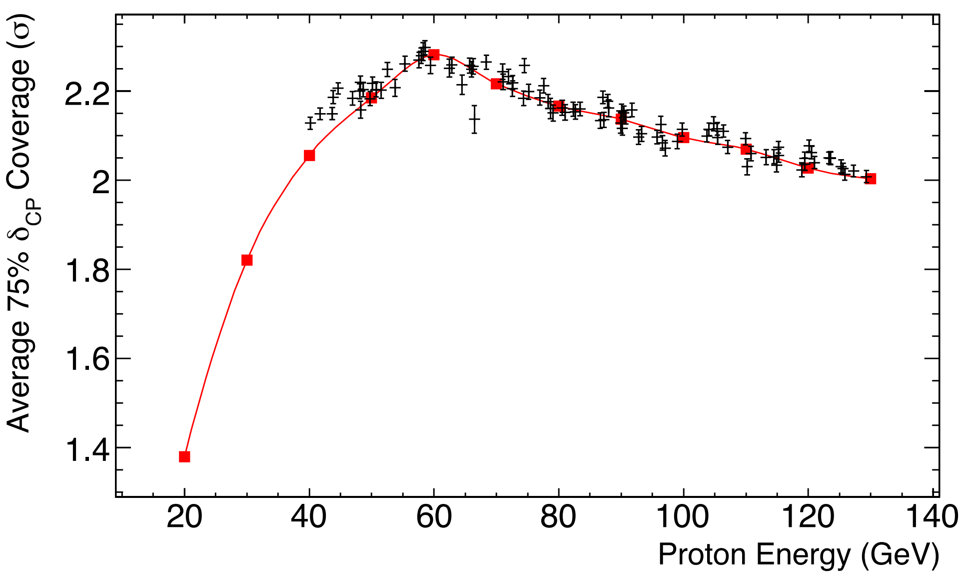
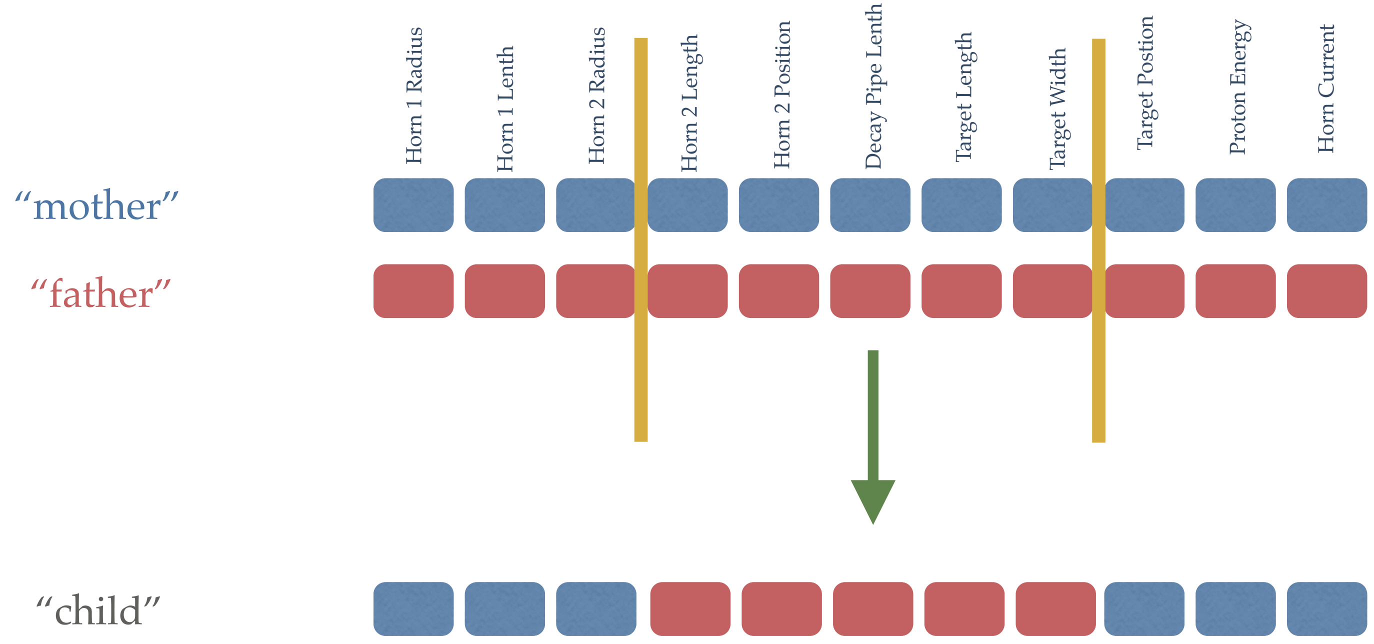


A comparison of an approximation with the actual CP sensitivity for different proton beam energies

But considering e.g. just 20 parameters, each with 20 possible values, scanning over the available phase space would take much **longer than the lifetime of the universe**, even with very fast simulations.

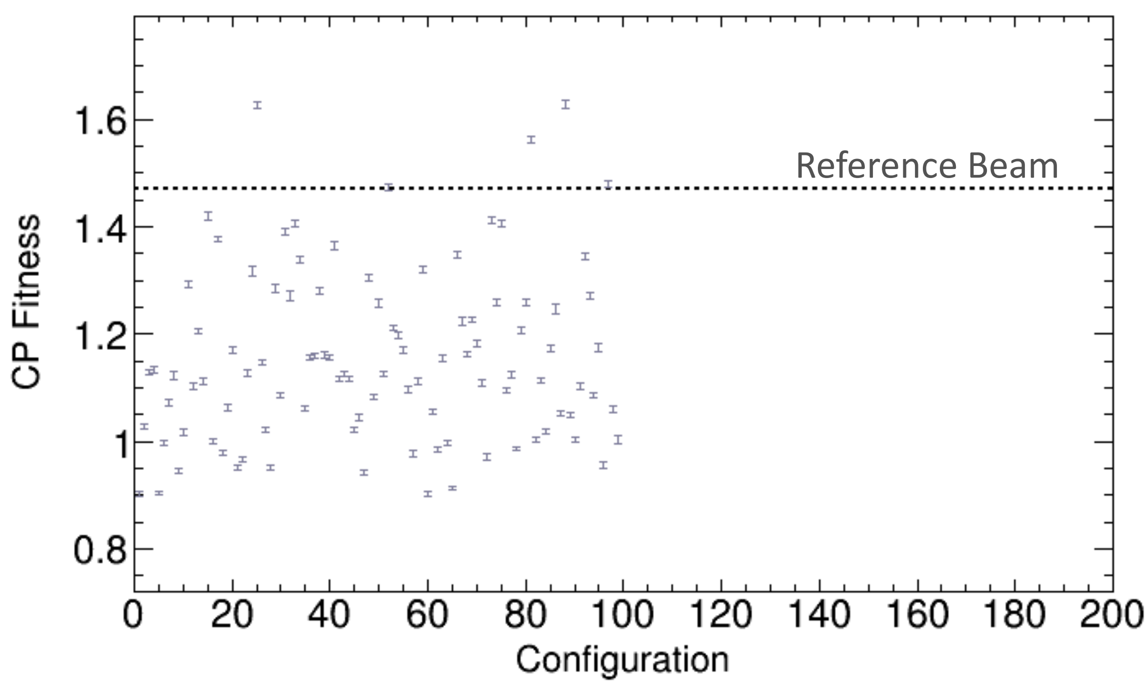
Genetic Algorithms

- Since we wanted to build the beam sometime in our lifetimes, we developed a genetic algorithm
  - A beam configuration is viewed as an organism; you start with a sample of randomly chosen organisms
  - Configurations are judged based on “fitness” (CP sensitivity) and best configurations are mated together to form new (and better) designs



Genetic Algorithms

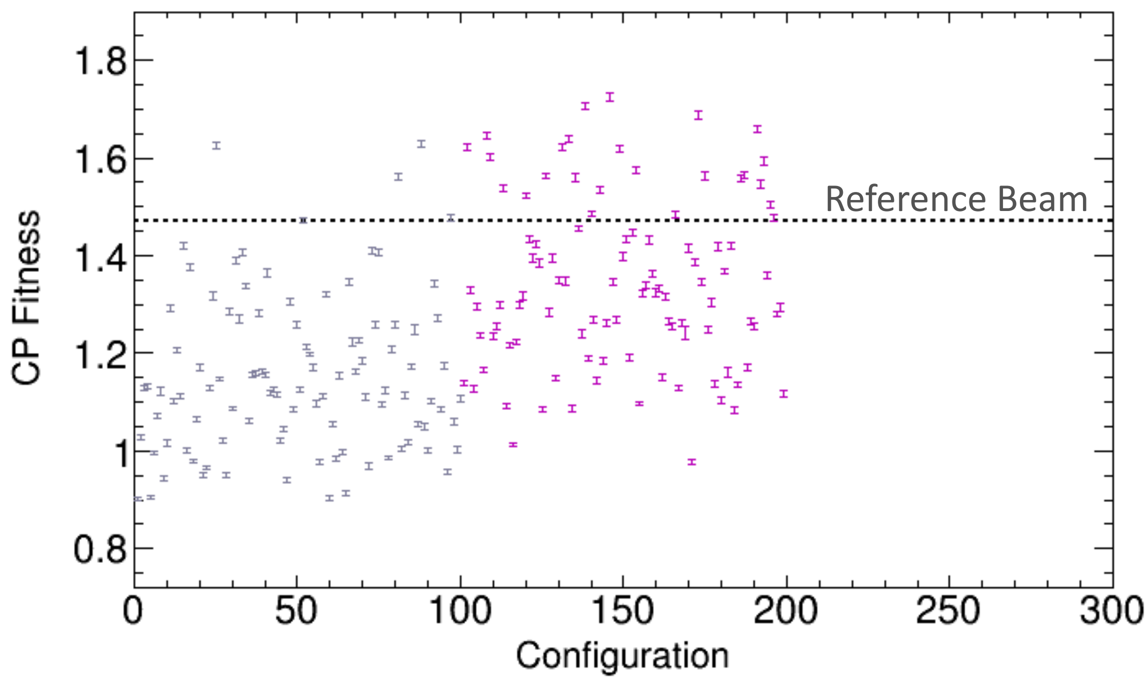
- The initial set of randomly chosen beams is generally pretty poor:



But when you take the best ones, and mix them together…

Genetic Algorithms

- Pretty much immediately, you start to do a lot better:



And then you repeat this survival of the fittest procedure over and over again

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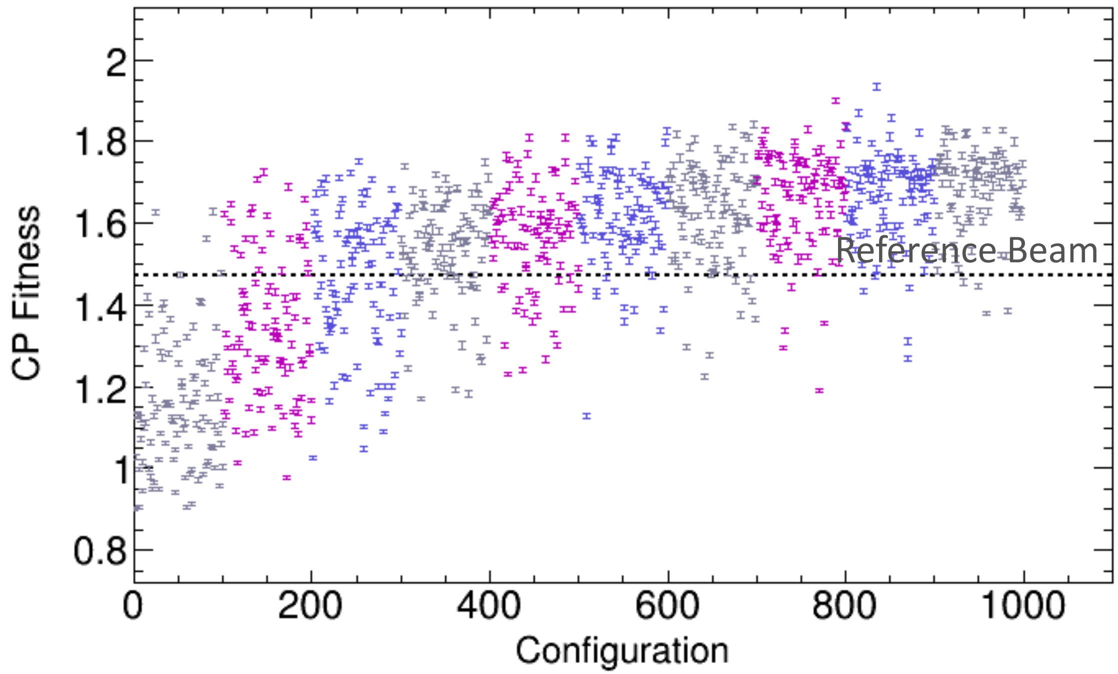
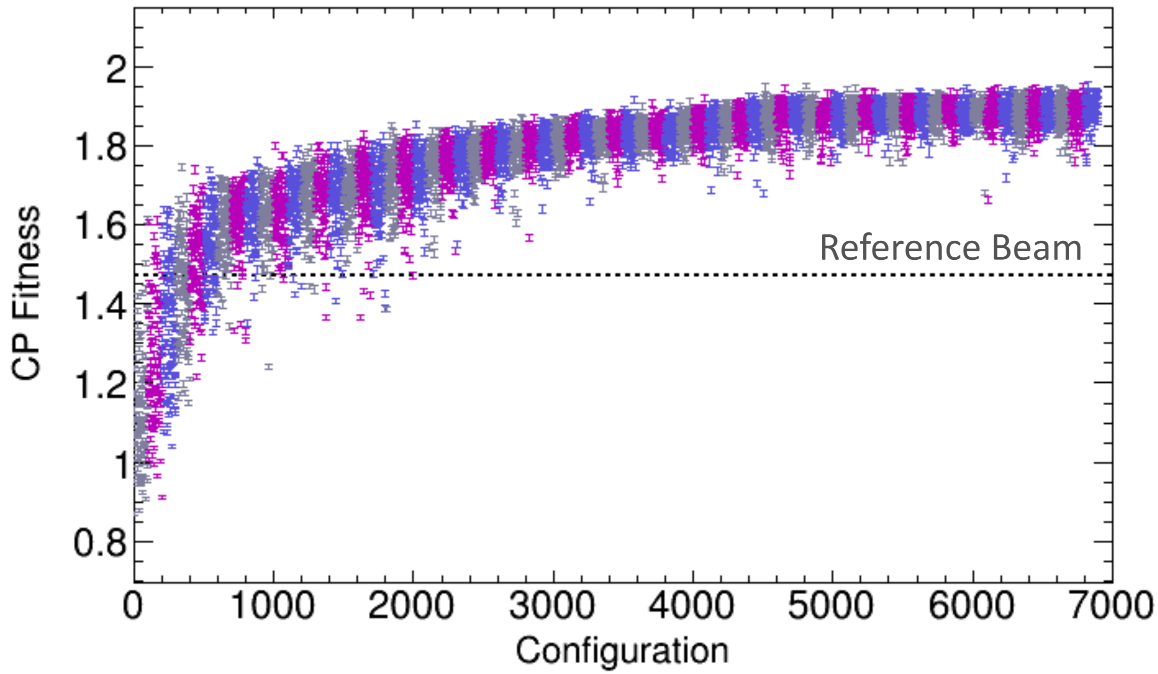


And then you repeat this survival of the fittest procedure over and over again

Genetic Algorithms

- Eventually, the algorithm converges on an optimal beam design
  - Each generation runs in parallel on the Fermigrid and takes ~ 2 hours; convergence takes a few weeks

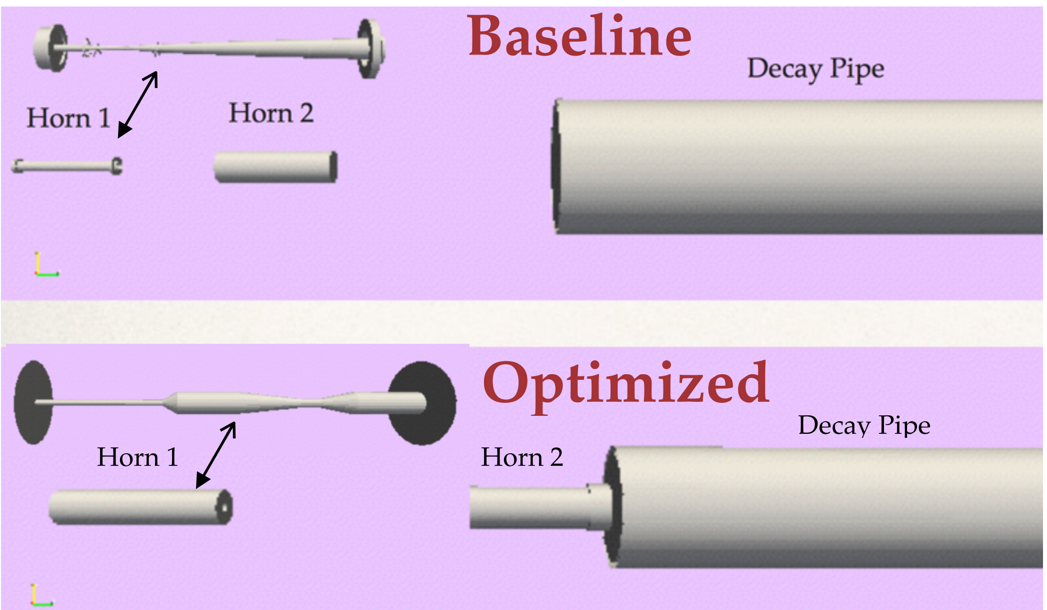


We know that this algorithm produces good beam designs.

We can never know that it gave us the best possible design

Initial Results

- Our first attempts at optimization considered a two-horn system

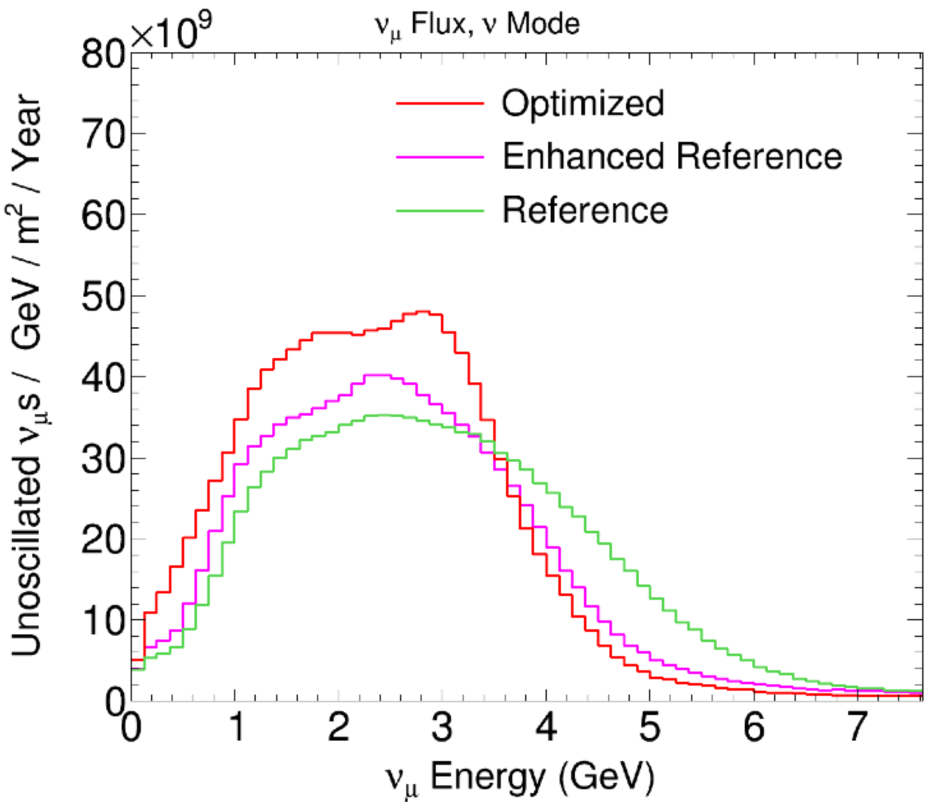


Features of optimized focusing system:

- Very long first horn
- Long (2.5 m) target
- Larger second horn
- Greater horn separation
- As much horn current as possible

Initial Results

- It was clear that we were on the right track — the neutrino flux (and physics sensitivities) were much improved:



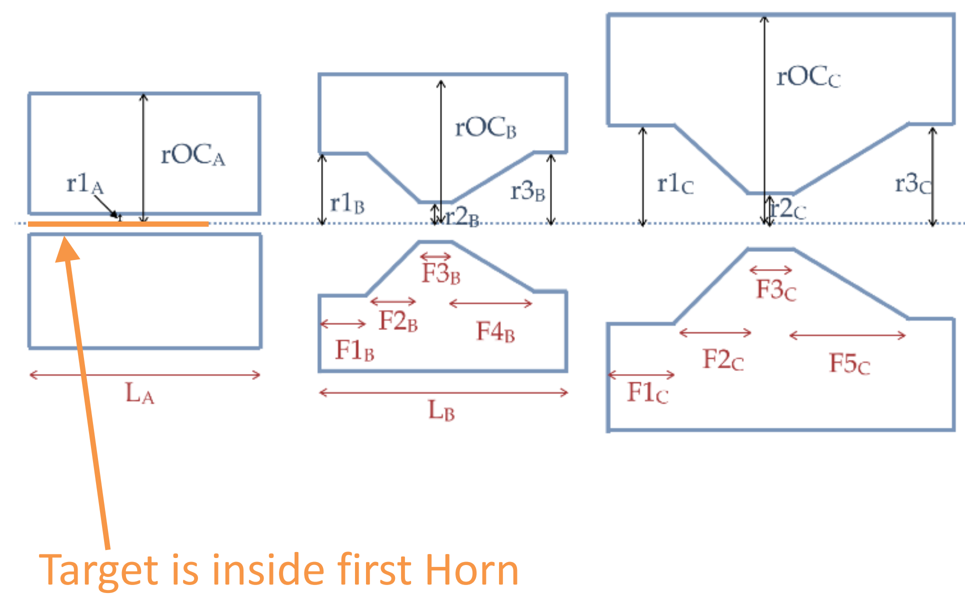
The problem at this point was that the engineers were pretty sure they could not build the giant horns/ targets that came out of the optimization (while still satisfying other requirements of the experiment)

Iteration with Engineers

- So we embarked on many more rounds of optimization, incorporating realistic engineering constraints

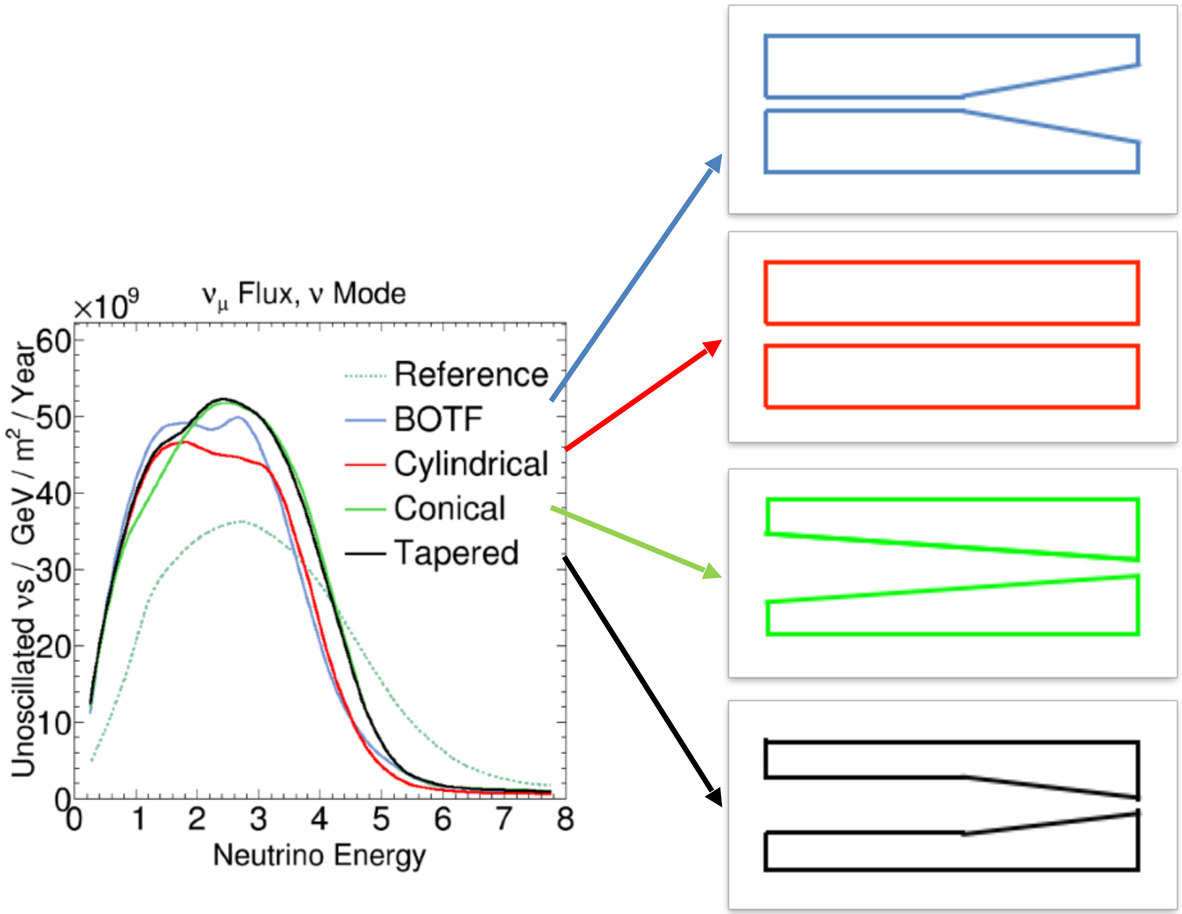
Engineering constraints considered

- Split first horn into two horns
- Target length limited to 2 m
- Horn size limited
- Horn system constrained to fit into ~21 m target chase
- Realistic inner conductor thicknesses



Iteration with Engineers

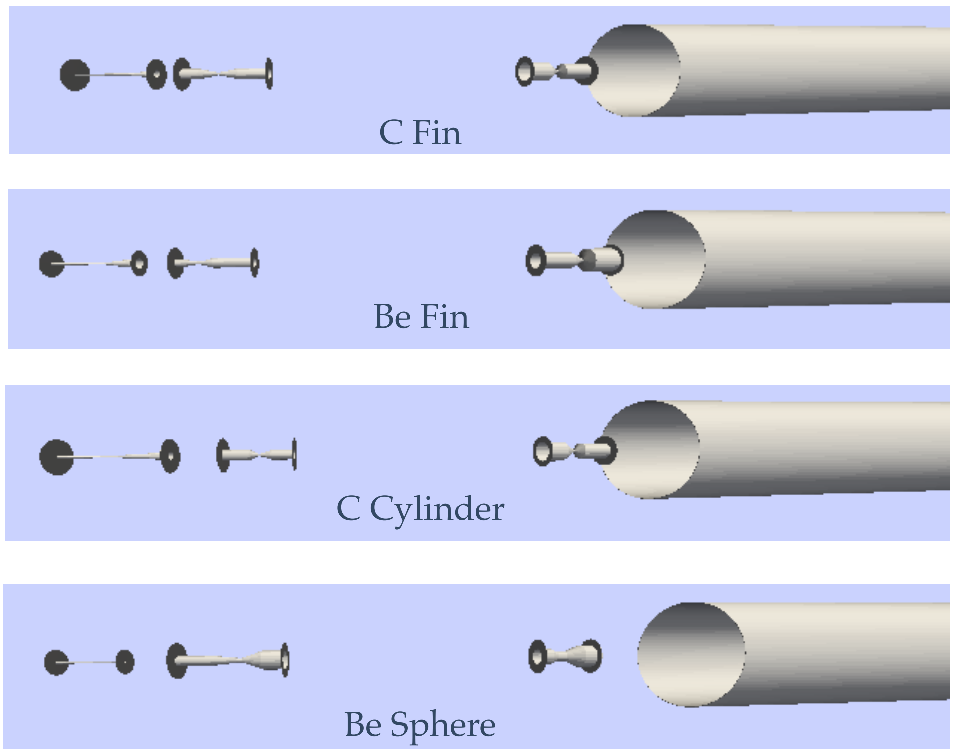
- We also considered a bunch of options for the shape of the first horn



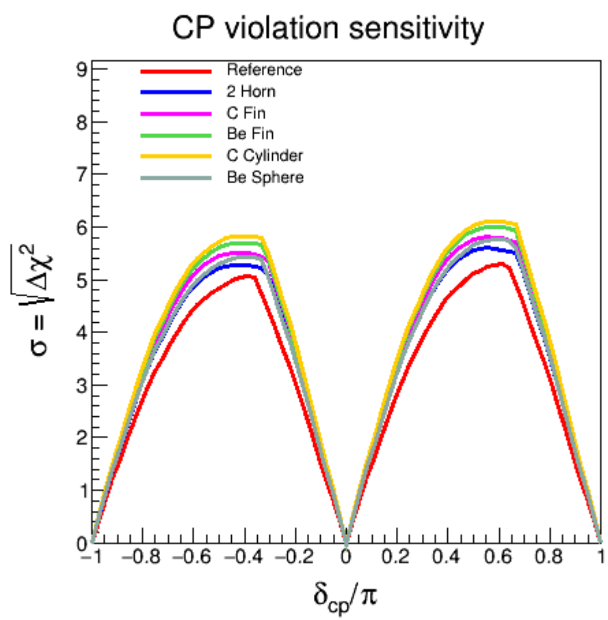
- Engineers expressed preference for more simple inner conductor
- See slightly better performance with more complex shapes — flared or tapered shapes vs cylindrical or conical inner conductor

Iteration with Engineers

- And ran optimizations with a several different target options:

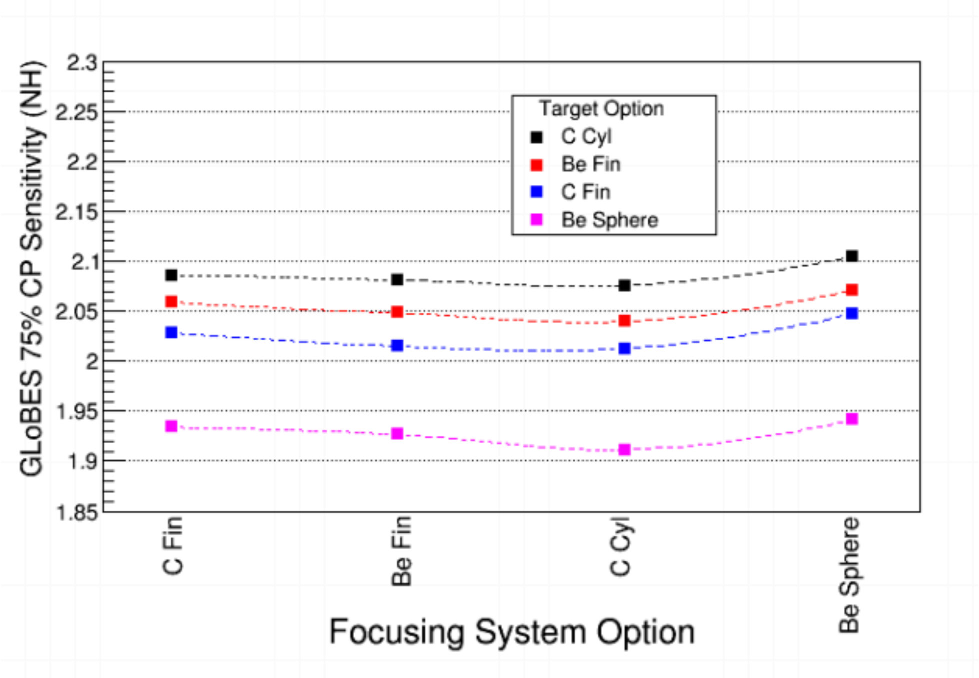


Different targets caused the optimization to find slightly different focusing systems. Some combinations are better than others, physics-wise



Iteration with Engineers

- Further investigation of optimizations performed with different options:

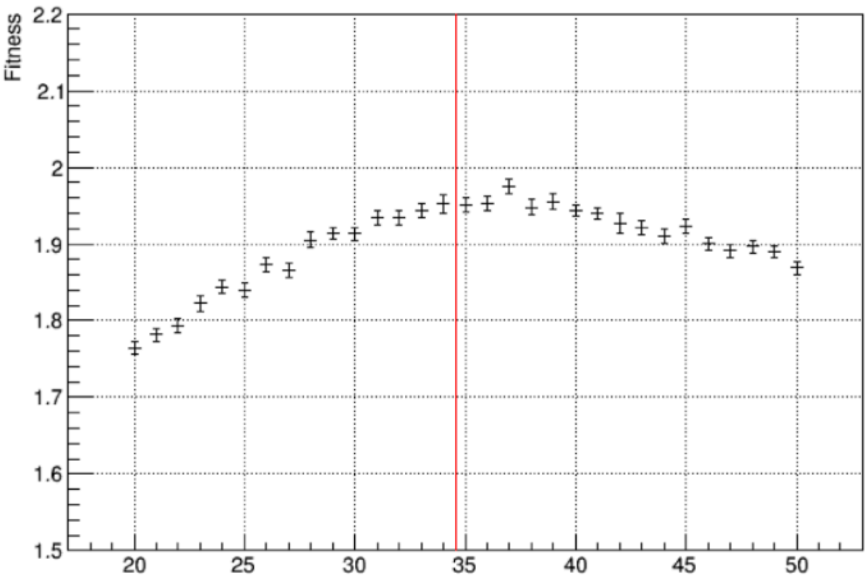


Difference in physics performance was primarily due to the target itself, not focusing system.

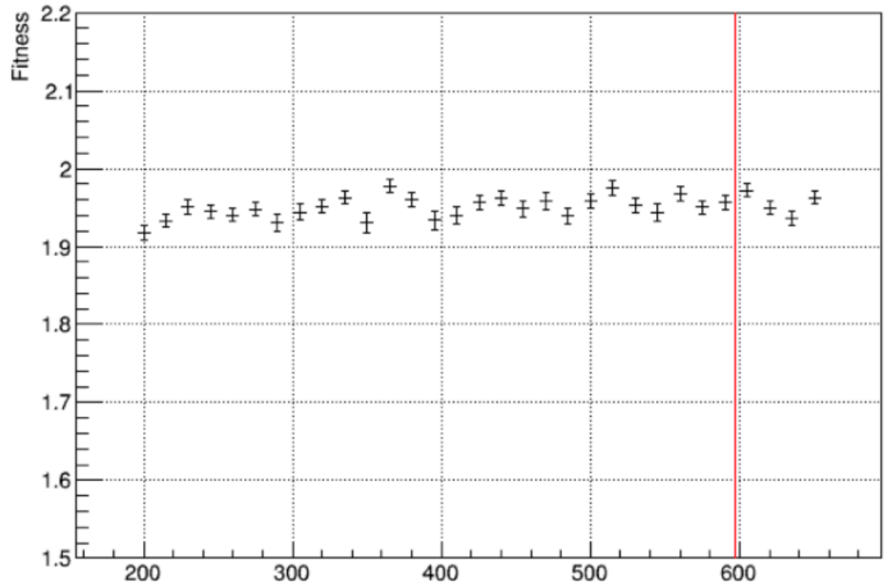
Cylindrical and Sphere targets here do not have complete material description, so this is not an apples-to-apples comparison

Iteration with Engineers

- Parameter scans were useful for understanding optimized systems:



Horn A Neck Radius in mm



Horn A OC Radius in mm

Iteration with Engineers

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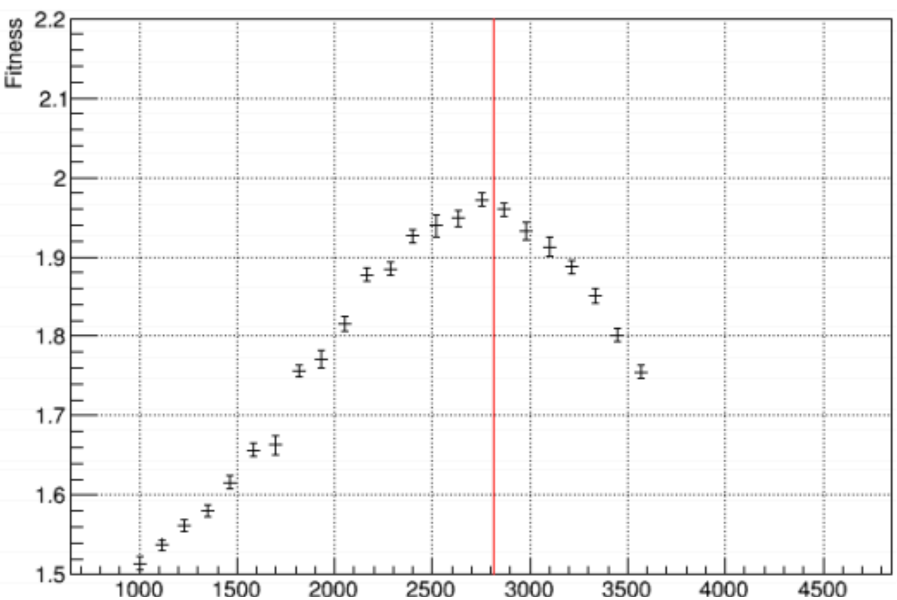
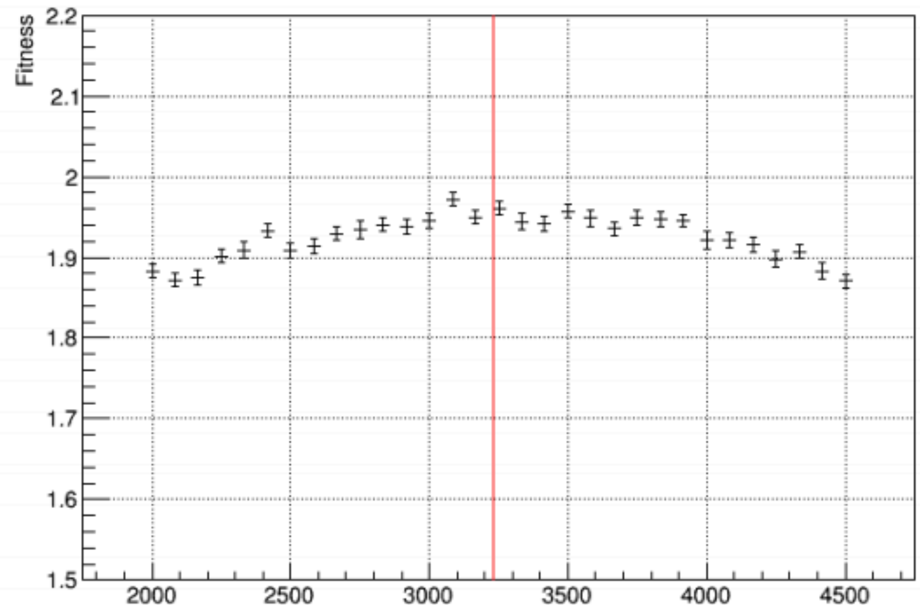


Horn A Length in mm



Horn B Length in mm

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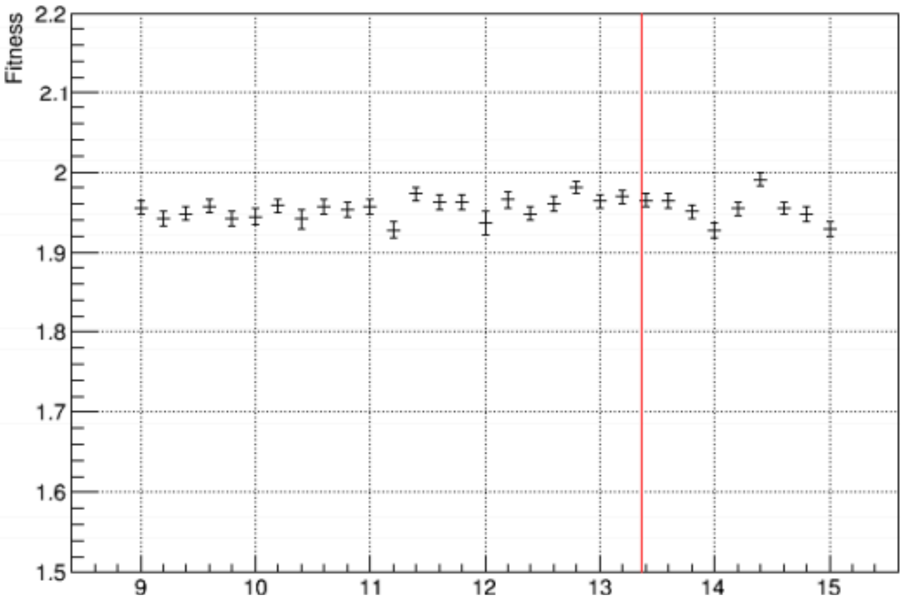
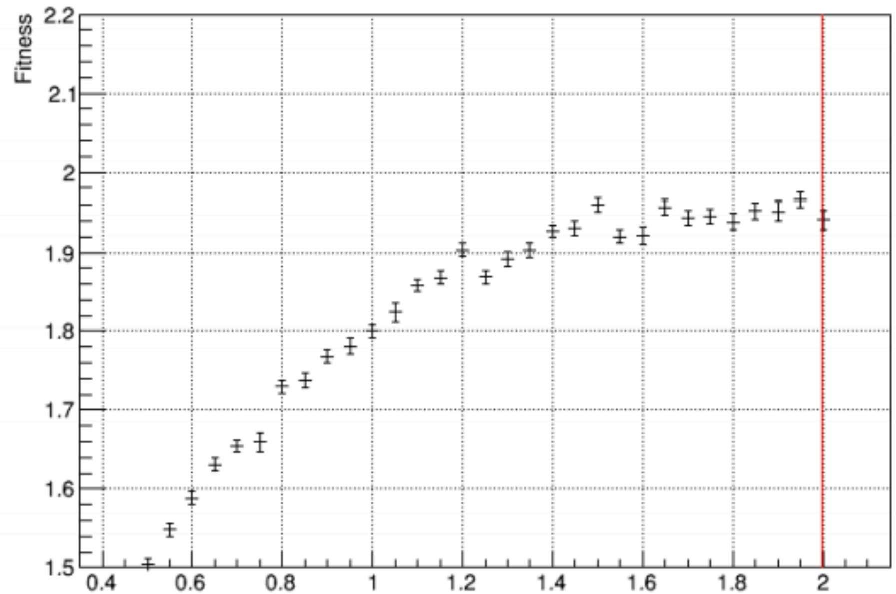


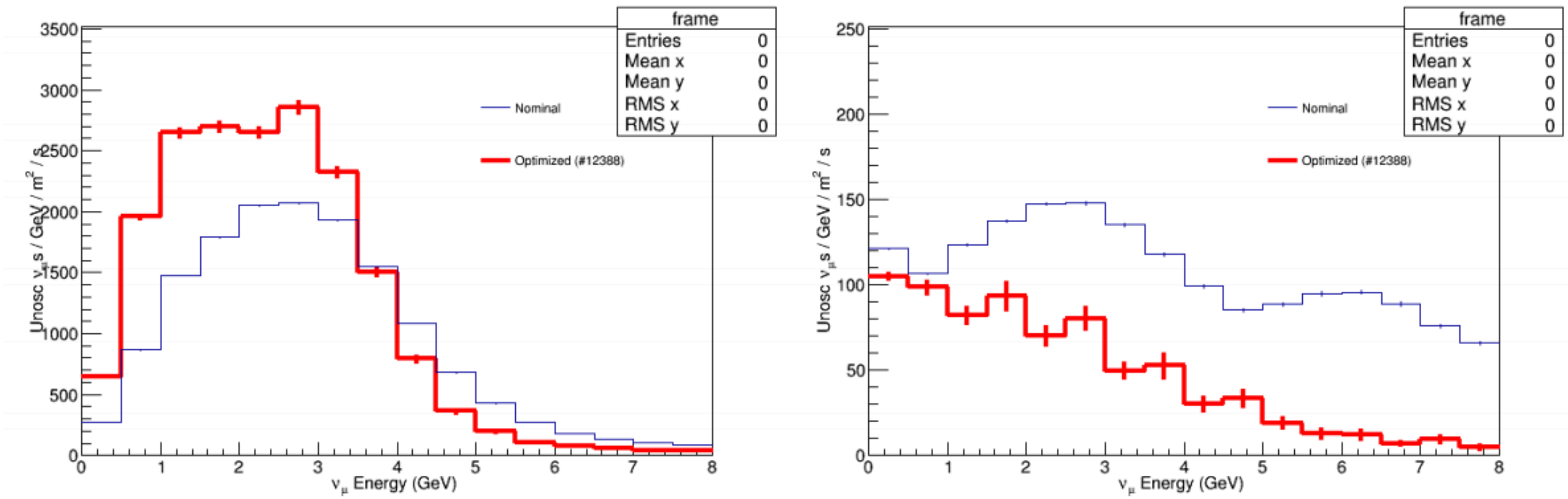
Target Fin Width in mm



Target Fin Width in m

Iteration with Engineers

- Subdominant neutrinos matter too



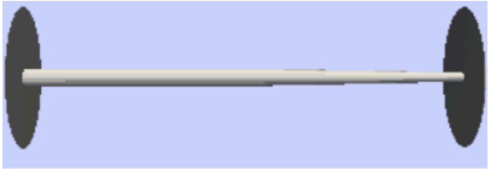
In many cases, improvements to CP-sensitivity is due not only to increases muon neutrino flux (and muon antineutrino flux in antineutrino mode), but also reductions in neutrino backgrounds in antineutrino mode ("wrong-sign" backgrounds")

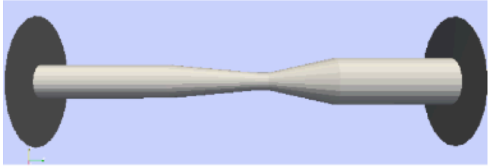
Final Idealized Design

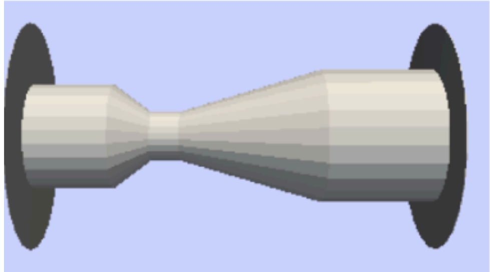
- We ultimately chose to pursue the focusing system with the best CP sensitivity of all of our optimized beams:

Features of final idealized design

- Short first horn, slightly tapered
- Long (nearly 4 m) second horn
- Wide third horn
- 2 m long target
- 300 kA horn currents
- 110 GeV proton beam





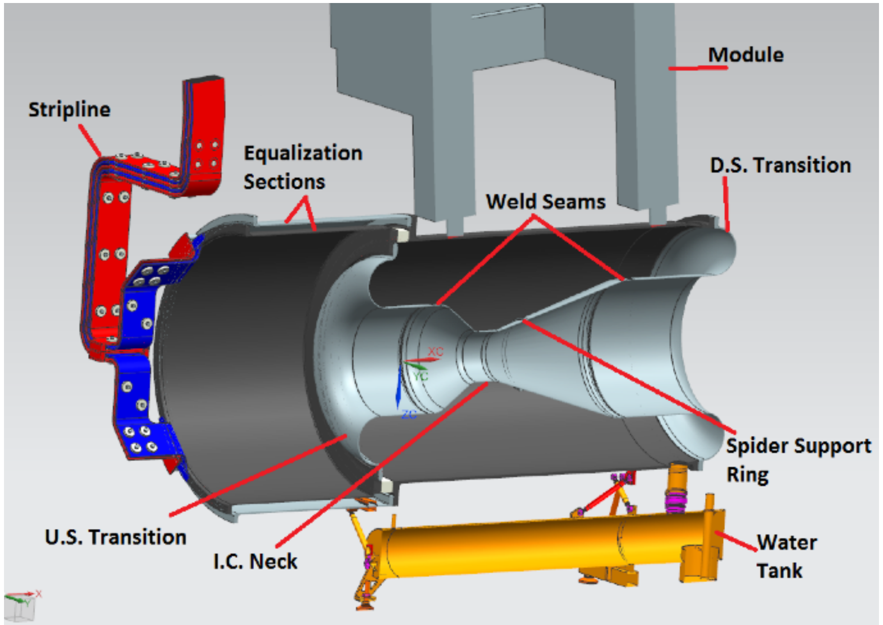


Toward Reality

- The optimized horns at this point were basically sheets of aluminum with 300 kA but no cooling or supports
  - We turned the design over to engineers to add necessary details of real horns

It wasn’t possible to include details like full support/cooling systems in the simulation used for the optimization

These elements were expected to have a modest negative impact on the performance of the beam (more material = less neutrinos)



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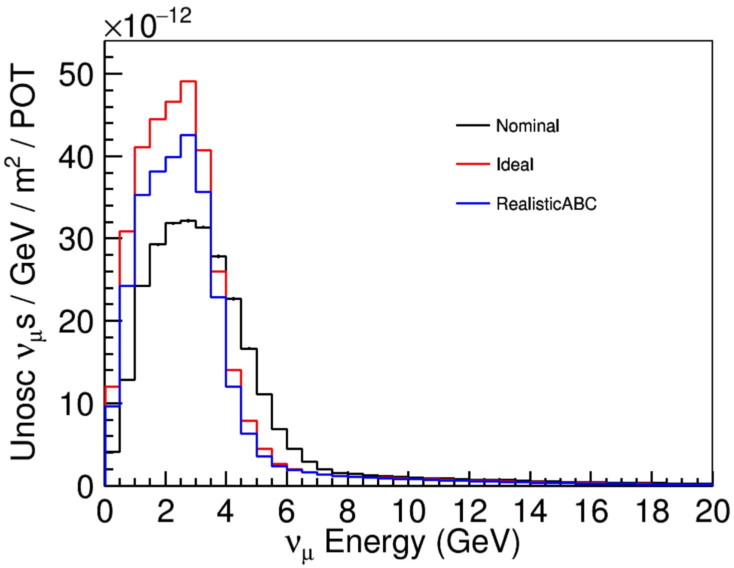
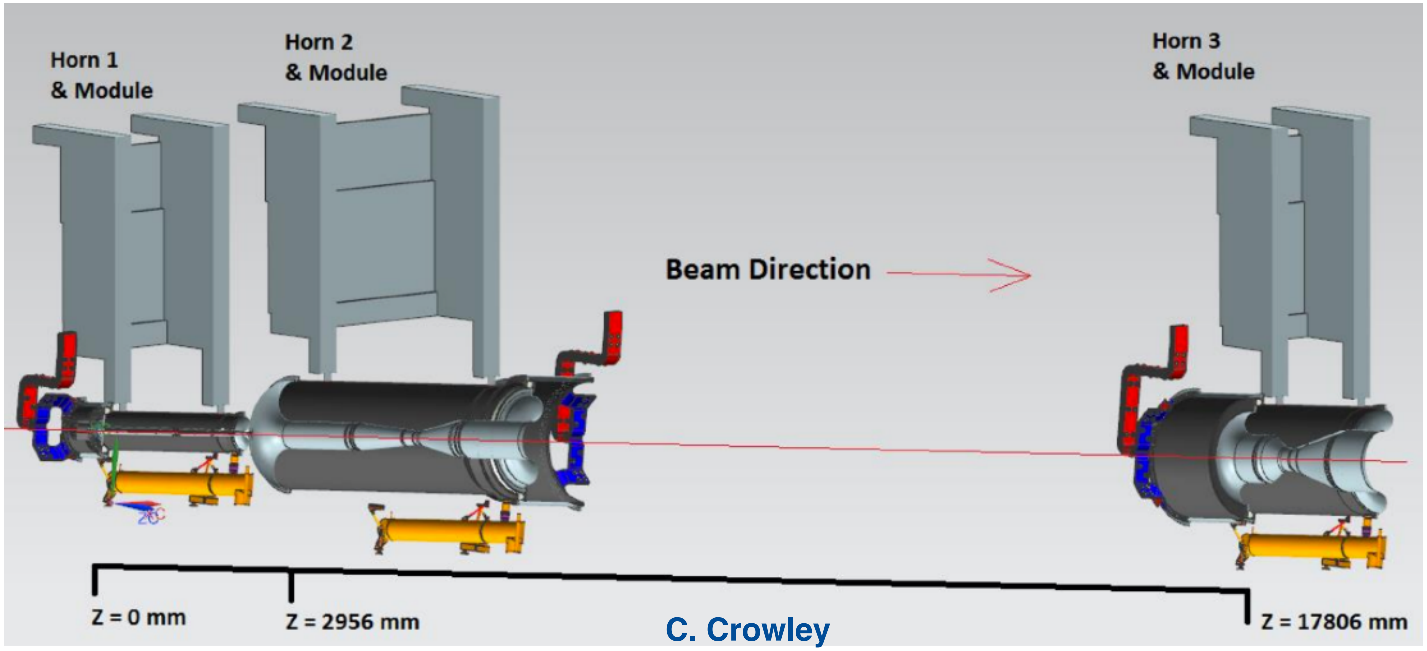


Initial results showed big losses in neutrino flux and physics performance

What we learned:
Most losses came from a “game of telephone” between engineers and physicists
Also, some came from extra material in the beamline — inner conductors and target supports

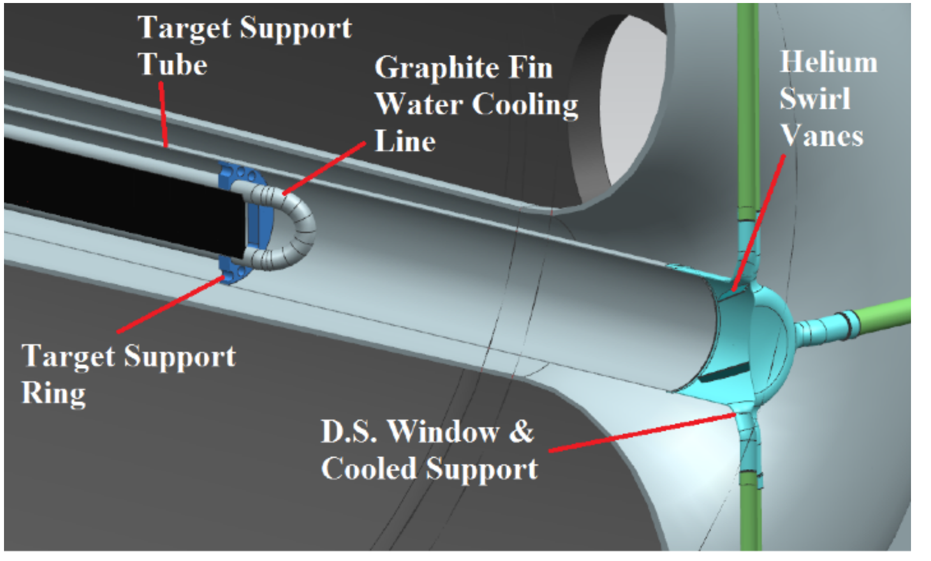
Toward Reality

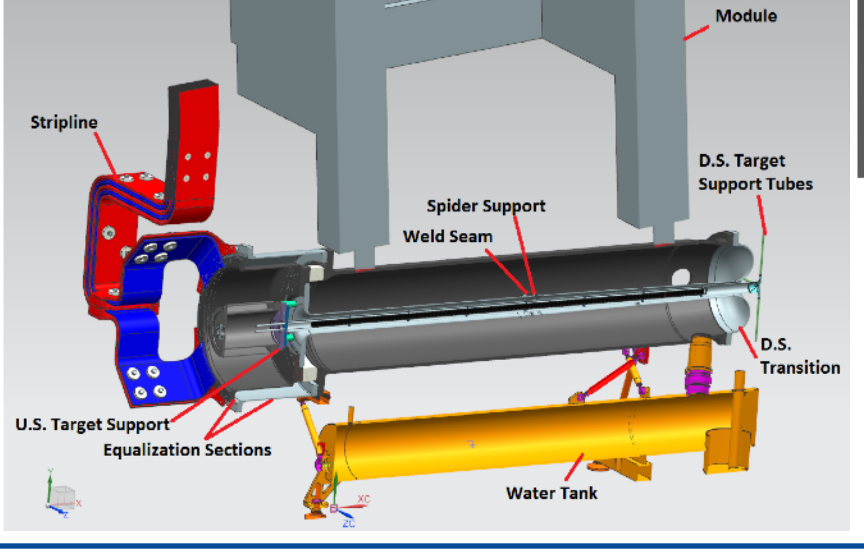
- Engineers then produced a second iteration, taking into account the lessons learned from the first round



Toward Reality

- Engineers then produced a second iteration, taking into account the lessons learned from the first round
  - 2 m target is fully integrated into Horn A
  - Target body & cooling lines are held by support rings inside a titanium tube.

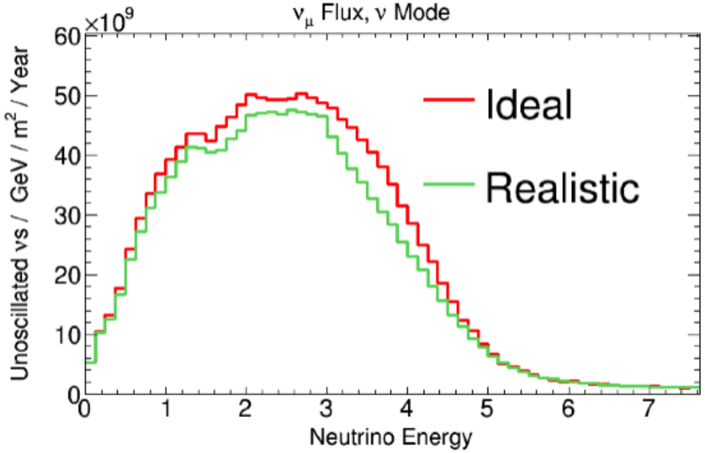


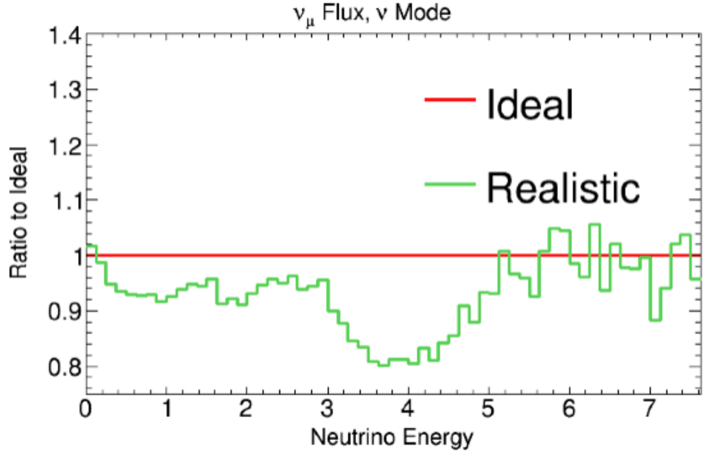


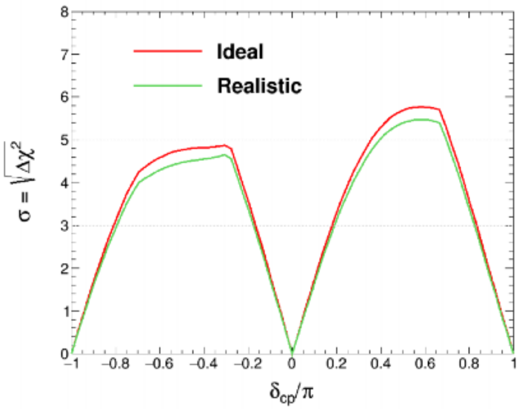
  - Helium flows through support tube from upstream end for heat removal.

Toward Reality

- Flux/physics losses this time were quite modest:

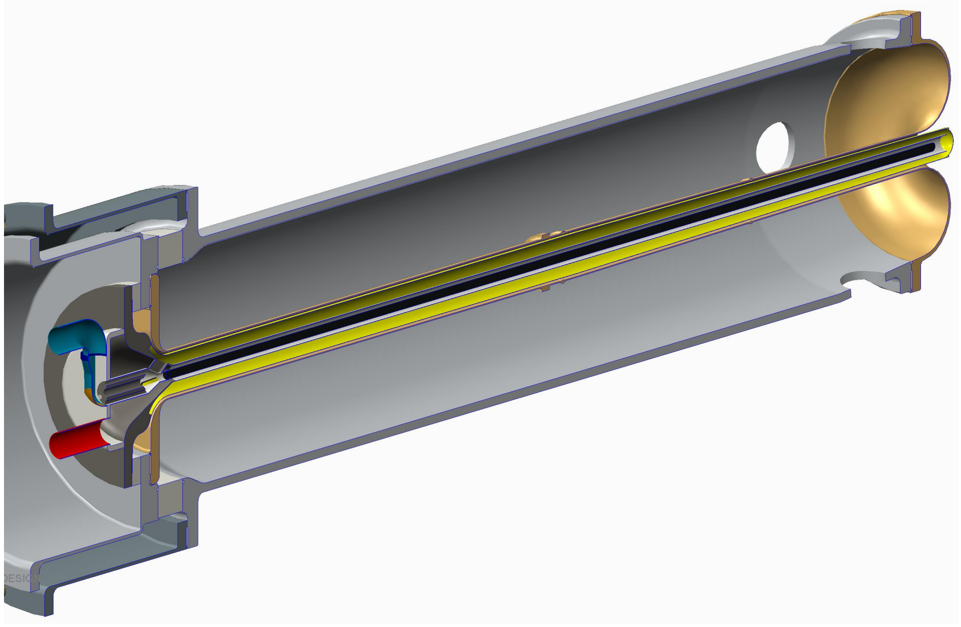


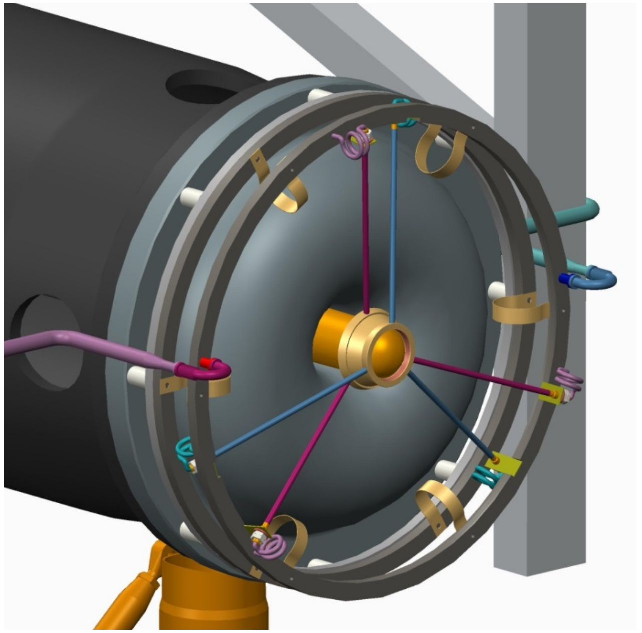




Toward Reality

- And those losses were mitigated by a new target design:

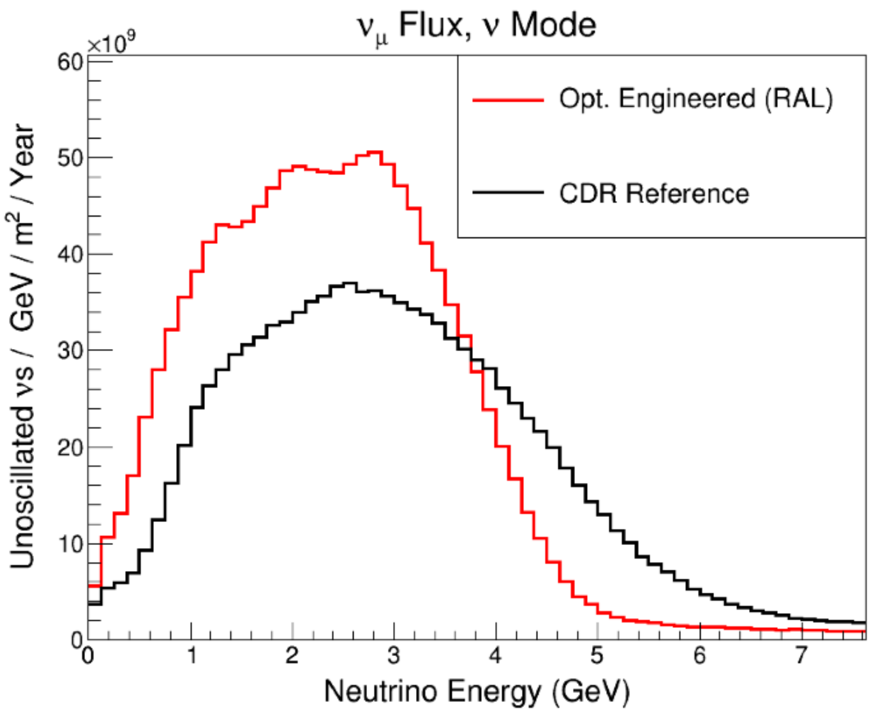


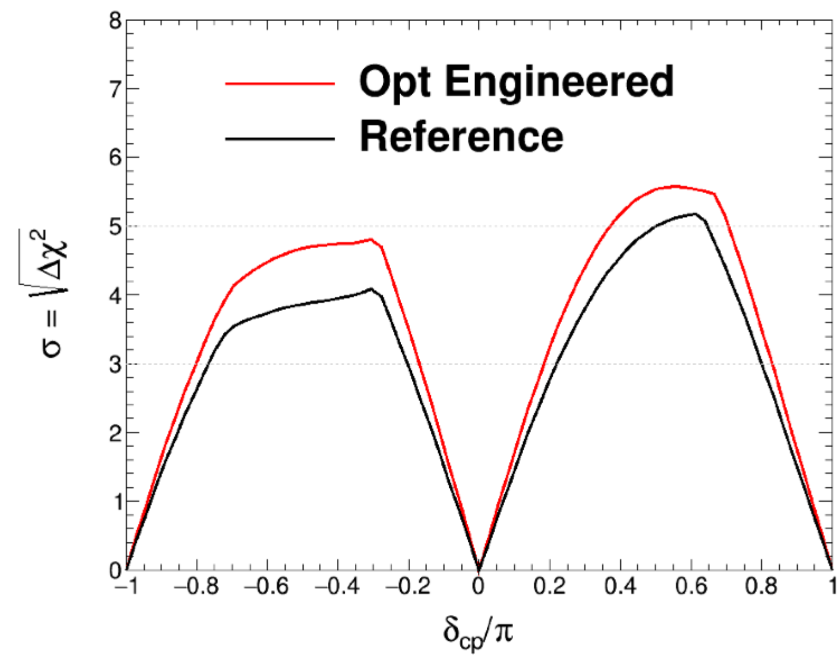


  - After optimization, a carbon cylindrical design was developed at RAL
  - Have studied two options — 2.2 m long cylinder w/ cooled support (current nominal design), and 1.5 m without support

Toward Reality

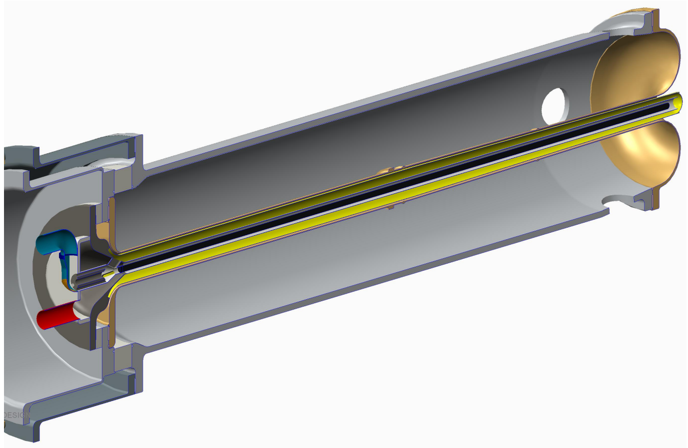
- And that brings us back to the optimized beam I described at the beginning of the talk:





Next Steps

- The optimized target/horn system is currently at the level of Conceptual Design
- Will proceed to Preliminary Design over the next few years
- Will be critical to simulate design changes and minimize losses in beam performance



  - Target design still under consideration
    - 1.5 m target?
    - Two cantilevered half-targets?

- Have also maintained genetic optimization software to re-optimize parameters and study possibilities for long-term physics goals such as tau neutrino appearance and Non-Standard Interactions

Next Steps: Particle Swarm Optimization

- We are also pursuing alternatives to the genetic algorithm:

"Particle Swarm" algorithms are used to simulate animals swarming in nature

Also turn out to be good optimization algorithms

Initial results indicate ~order of magnitude decrease in time to convergence over genetic algorithms

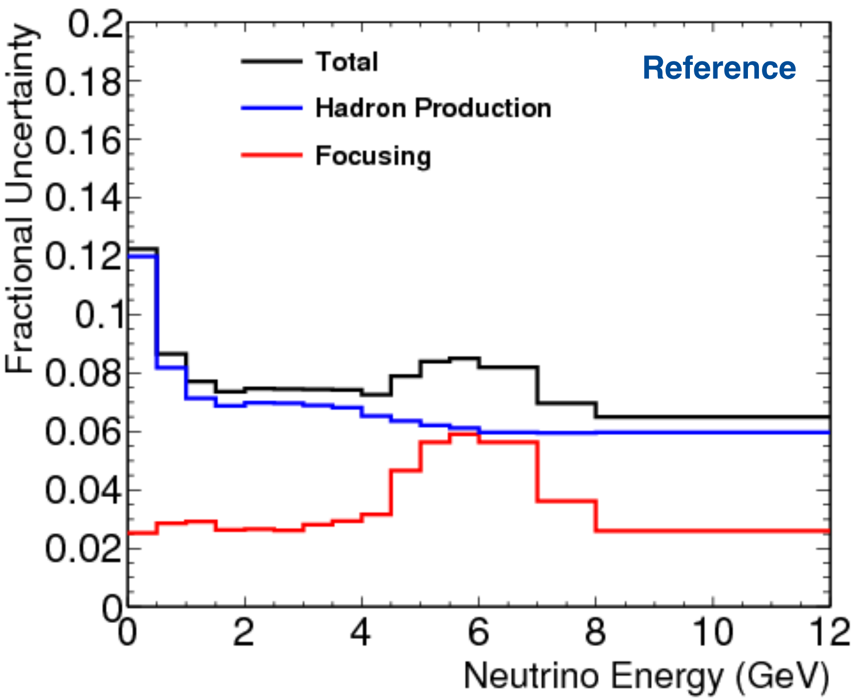
Conclusion

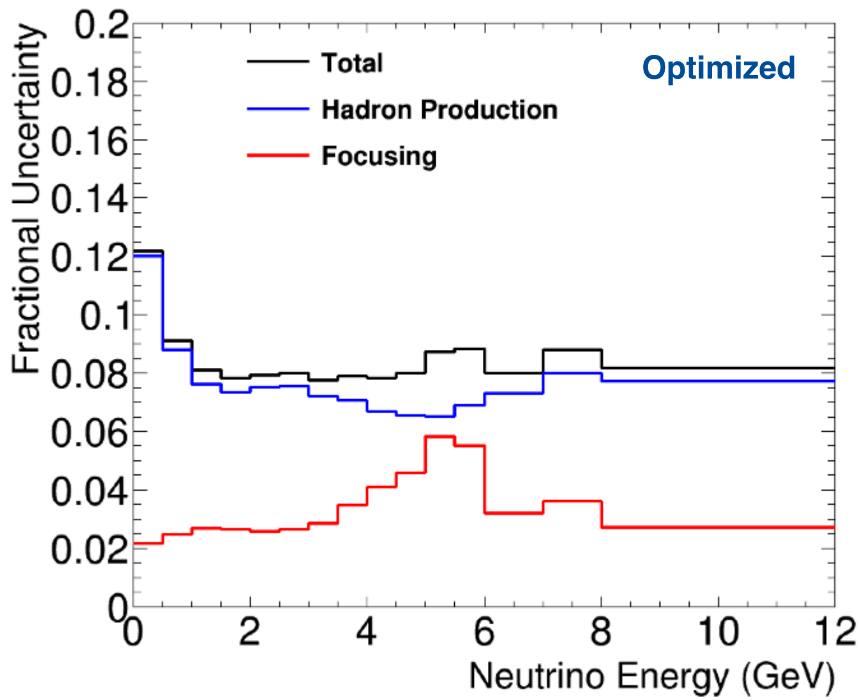
- The LBNF optimized design is the result of **several years of optimization and iteration** with engineers
- Final design yields **significantly better flux and sensitivity** to oscillation parameters than the Reference design
- Optimized beam is current **progressing to Preliminary design**
- **Optimization continues** for potential long term DUNE physics goals

Thank You!

Systematic Uncertainties of Optimized Beam

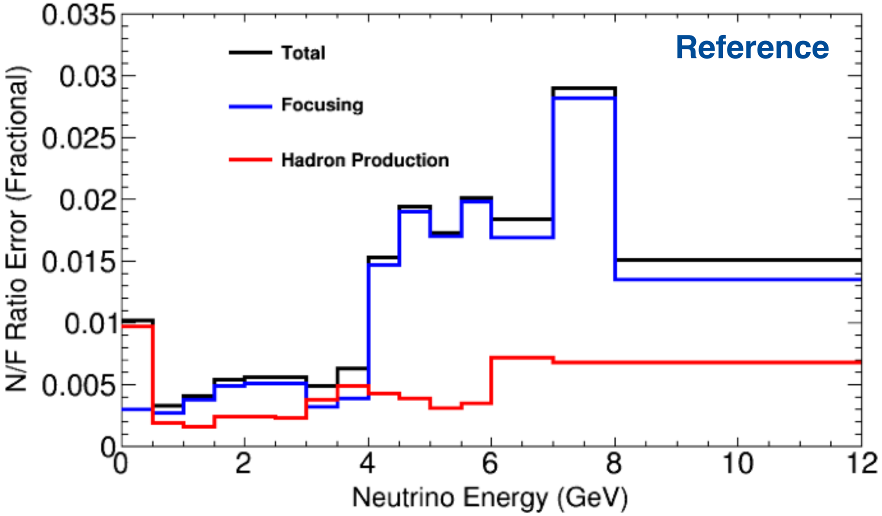
- Also studying uncertainties on neutrino flux with optimized beam
  - Estimated using infrastructure developed by MINERvA

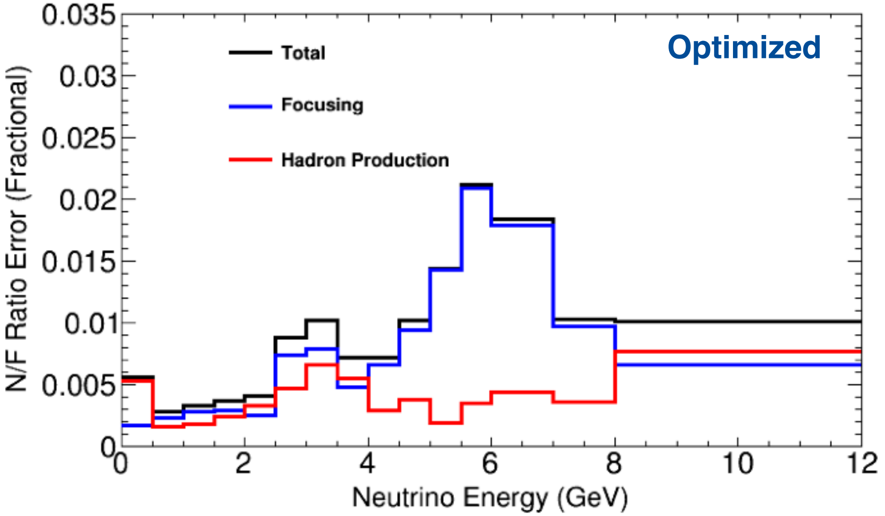




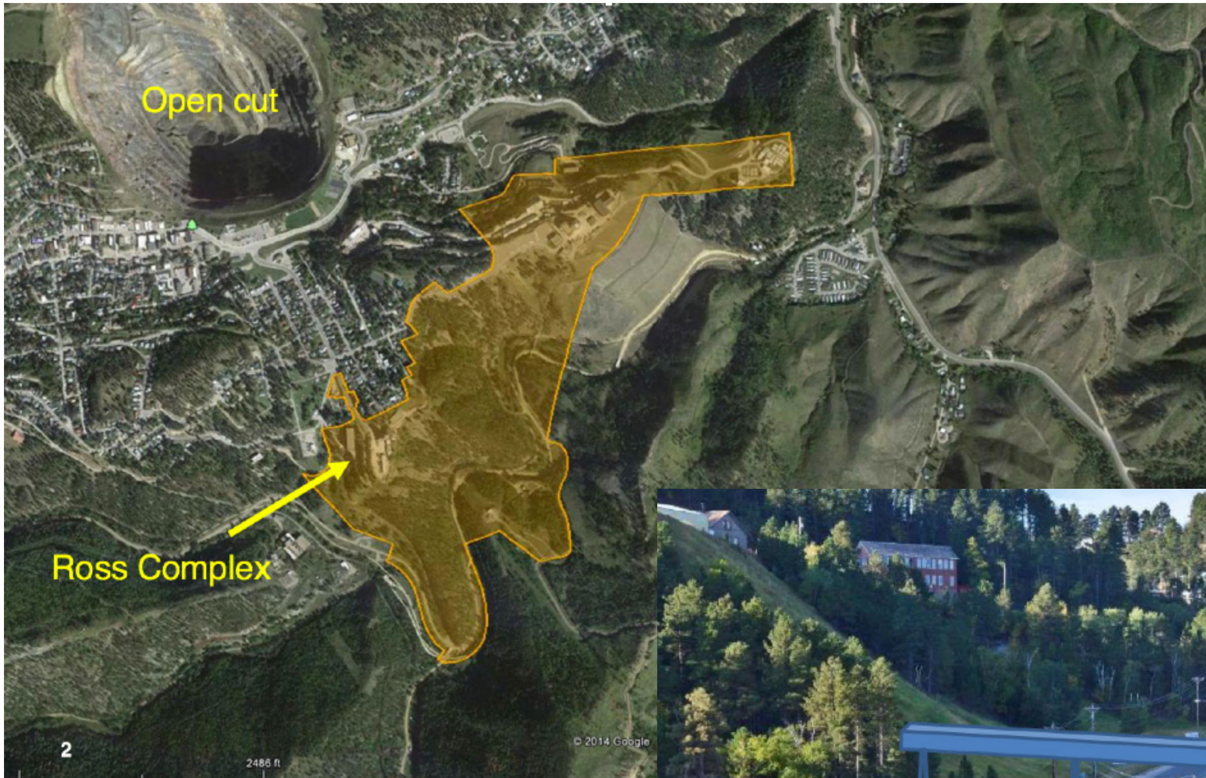
Systematic Uncertainties

- Uncertainty on near/far ratio (critical to oscillation measurements) is also similar:





LBNF/DUNE: Overview



875,000 tons of rock will be moved from shaft to open cut

Conceptual illustration of rock conveyer. Construction begins this year; ~3 years of rock-moving expected

LBNF/DUNE: Overview

Construction has begun!

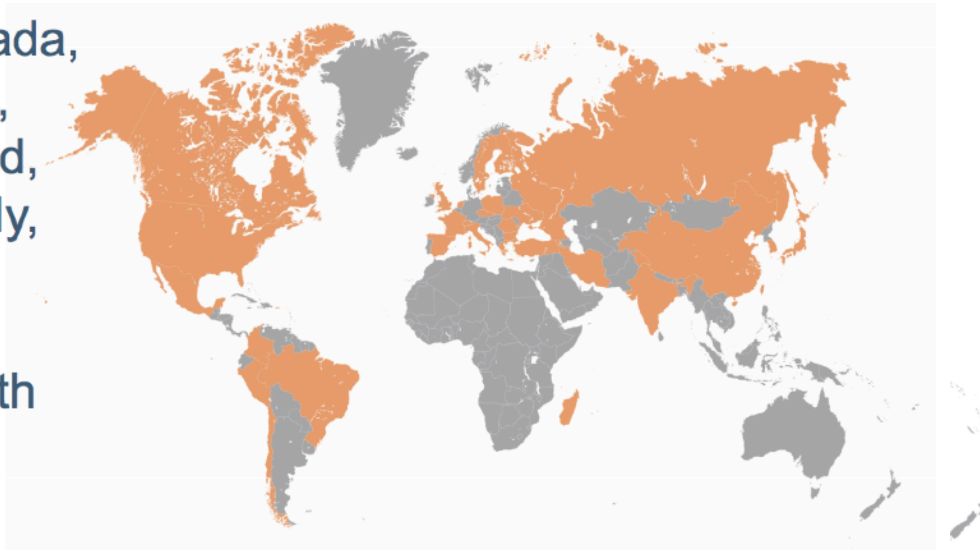
LBNF/DUNE: Overview

As of today:

60 % non-US

1095 collaborators from 175 institutions in 31 nations

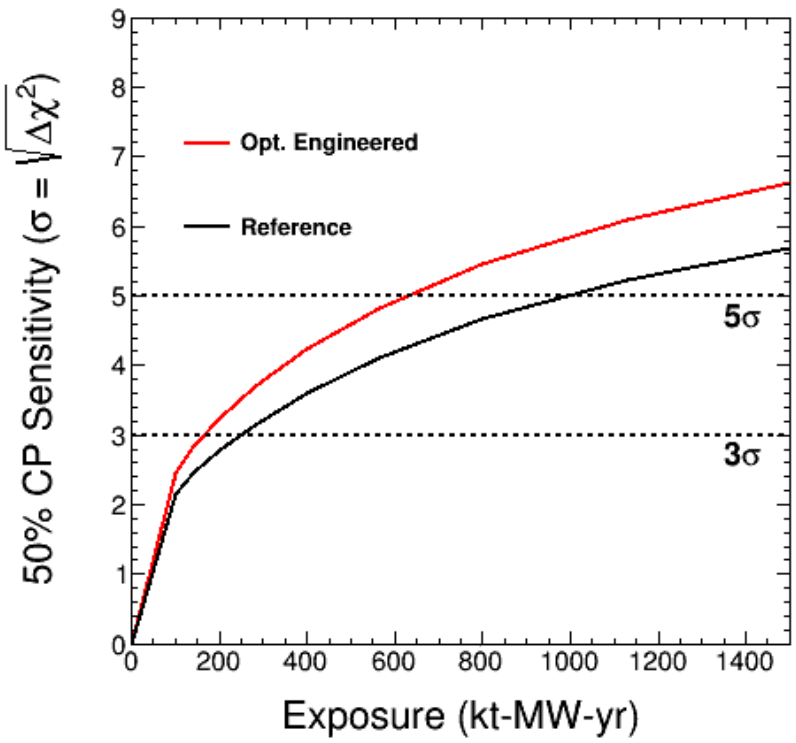
Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Spain, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Romania, Russia, South Korea, Sweden, Switzerland, Turkey, UK, Ukraine, USA

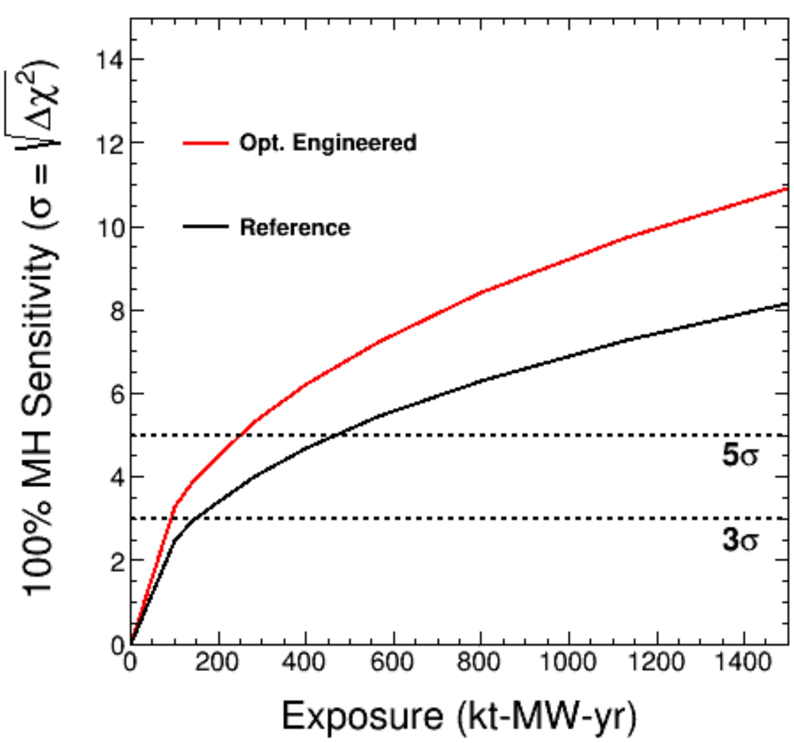


DUNE: a fully international science collaboration
LBNF (Long Baseline Neutrino Facility): US(DOE)-hosted project with international contributions

Physics Performance of Beam Options

- Improvements are present for all exposures:





Sensitivities use CDR GLoBES setup and default parameters; CP sensitivity assumes a normal mass hierarchy

Physics Performance of Beam Options

- Comparison of a few milestones

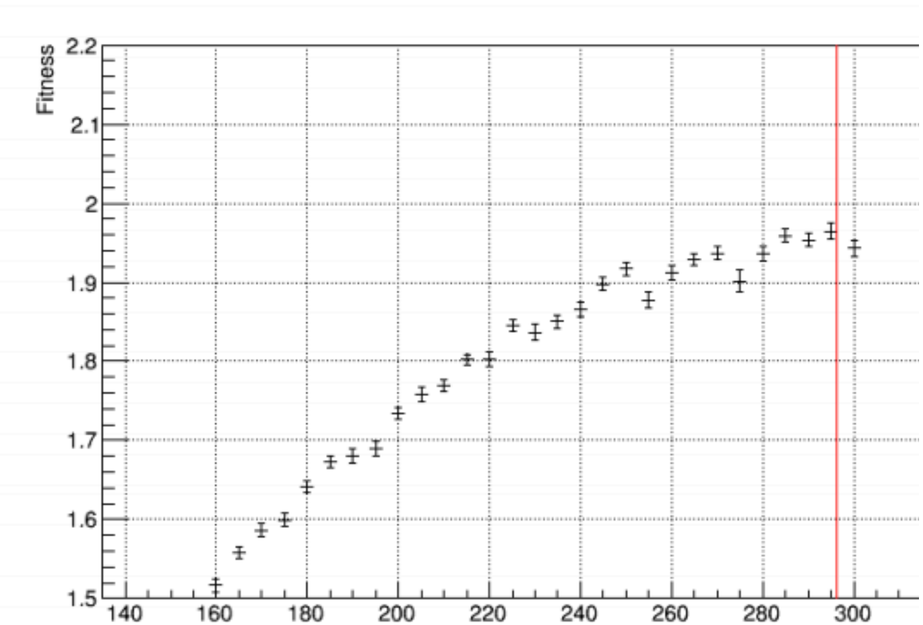
	Optimized	Reference	Improvement vs Reference
Time to 3 sigma 75% CP sensitivity (kT MW y)	921	1577	42%
Time to 5 sigma 25% CP sensitivity (kT MW y)	293	419	30%
100 % MH coverage @ 400 kT MW y (# sigma)	6.21	4.69	33%
$\sin^2 2\theta_{13}$ resolution @ 1000 kT MW y	0.0036	0.0043	18%
$\sin^2 \theta_{23}$ resolution @ 1000 kT MW y	0.0027	0.0031	12%

Equivalent to increasing mass of far detector by 70%, or 28 kTon

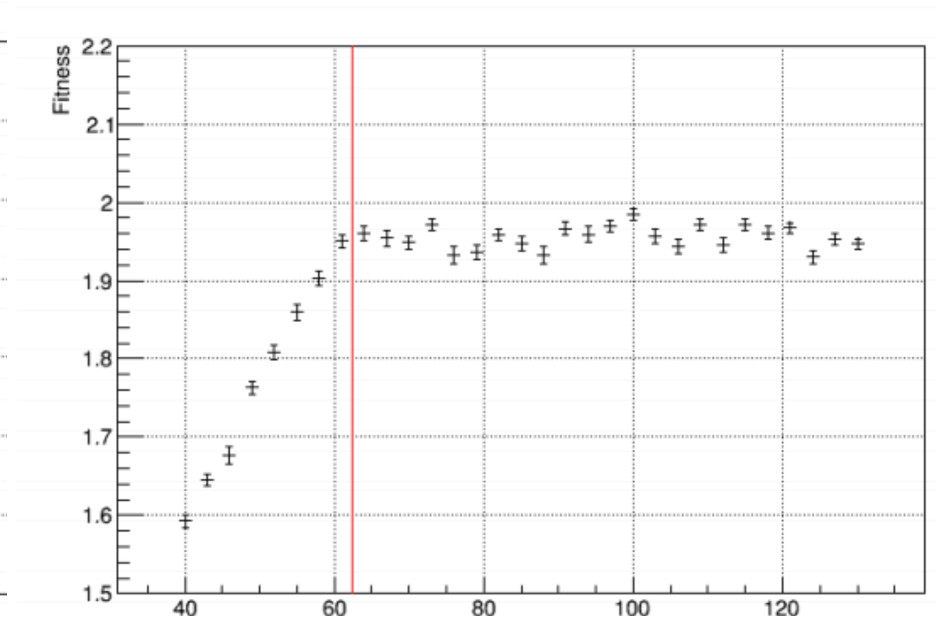
17 kTon of Argon

Beam Optimization

- Parameter scans were useful for understanding optimized systems:

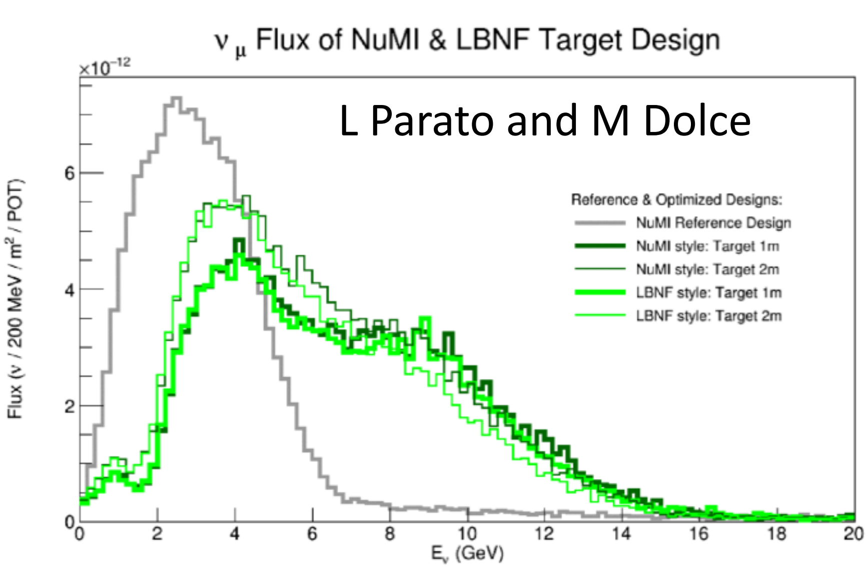


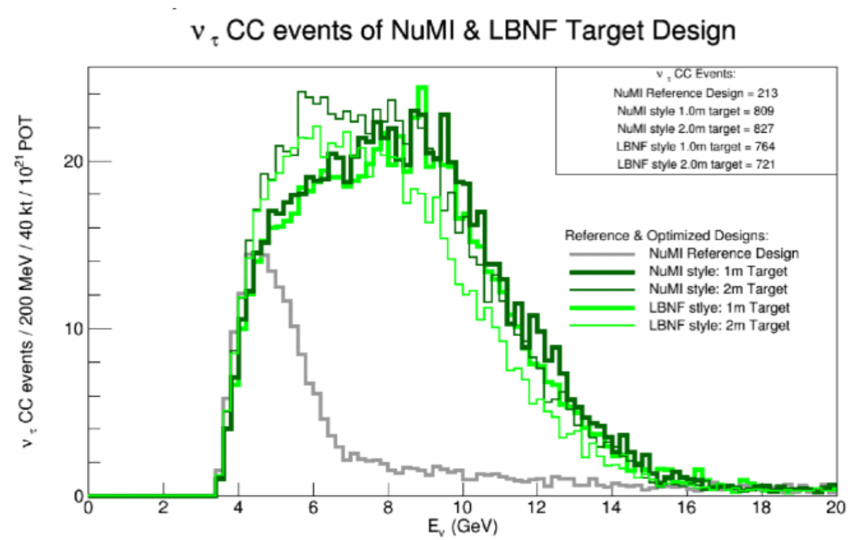
Horn Current (kA)



Proton Momentum (GeV)

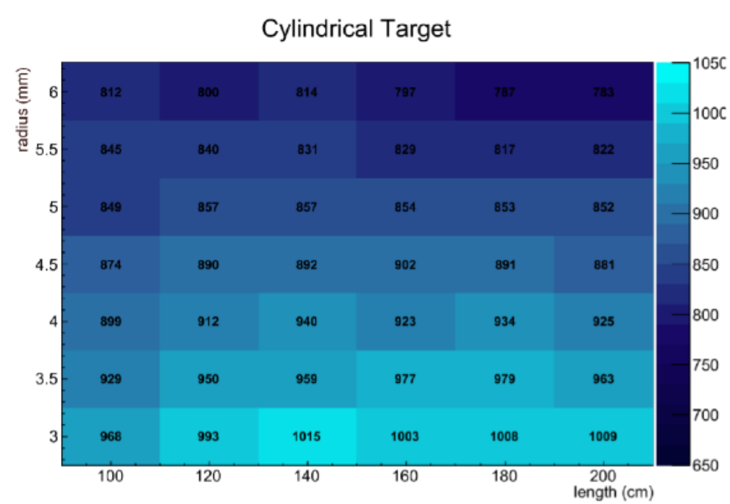
High Energy Optimization





$\sigma_{\text{beam}} = \text{target width}/3$

- Have done optimizations for **tau neutrino** appearance
- **~1000 events / year** possible with NuMI parabolic horns
- Slightly less with optimized horns
- Also beneficial for separating **CP/NSI**



Toward Reality

- Cylindrical target gives modest improvements to flux/CP sensitivity: